DEVELOPMENT OF THE DUOMORPH ASPHALT RHEOLOGY TESTER (DART): A SELF-CONTAINED, PORTABLE DEVICE FOR QUALITY ASSURANCE TESTING OF ASPHALT BINDERS

BY

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DISSERTATION

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ABSTRACT

This dissertation developed a bench prototype device, named as the Duomorph Asphalt Rheology Tester or DART, for use in quality assurance (QA) testing of asphalt binders. This self-contained, portable device was re-engineered from its original version developed in the 1970s to test the structural integrity of solid rocket propellant fuels. Central to the DART system is a circular piezoelectric duomorph or bimorph with strain sensors that record its response to an applied alternating current (AC) electrical voltage signal. The strain signal’s amplitude and lag relative to the drive signal vary as a function of the properties of the medium it is operating in. The goal of this research was to provide a methodology, using the outputs from the duomorph as a basis, to rapidly and cost-effectively test virgin and modified asphalt binders for specification compliance either at the refinery, the blending terminal, the asphalt plant, or at the job site. The DART was evaluated both as a surrogate test device to the Dynamic Shear Rheometer (DSR) and also as a device capable of directly estimating the AASHTO M320 Table 1 specification parameters—the complex shear modulus (G*) and phase angle (δ).

The first phase of the research evaluated the physical and operational characteristics of a prototype DART system and its feasibility to test asphalt binders. Various DART gage instrumentation techniques and piezo driving and grounding methods were also examined. It was determined that the DART gage and the associated electronics can withstand normal laboratory use for extended periods of time. Further the DART gage’s primary outputs—bending strains and phase shifts—were repeatable and correlated well with G* and δ. The gage responses were found to be unique to each asphalt binder grade tested thereby establishing the ability of the system to “fingerprint” asphalt binders and function as an effective QA tool. Finally, the range of asphalt binder storage moduli and phase angles over which the DART was system was effective was established.

The next phase involved making direct comparisons of the DART estimated G* and δ using an existing data reduction technique developed in the 1970s with those determined from the DSR. These comparisons indicated the need to develop a theoretical framework to more
accurately predict asphalt binder $G^*$ and $\delta$ from the DART gage responses. A finite element (FE) model was subsequently configured to simulate the gage behavior in air and when embedded in an asphalt medium. After establishing suitable load equivalencies, the finite element analysis was performed entirely in the mechanical domain. This was done primarily to reduce input complexity associated with performing a coupled piezoelectric-steady state analysis. The FE model’s results compared well with laboratory measured DART responses across a range of binders tested, thereby validating the model. A parametric study was then conducted using the FE model over a range of assumed asphalt binder viscoelastic properties to develop relationships between the DART’s outputs and the asphalt binder $G^*$ and $\delta$. The relationships were plotted in the form of a nomograph. A limited validation study conducted using the nomograph provide good agreement between the DART predicted $G^*$-$\delta$ and the corresponding DSR measured values confirming the validity of the proposed data reduction scheme.

This research concluded that the DART can be used as a surrogate test device to rapidly evaluate and “fingerprint” the quality of the binders in the field for AASHTO M320 specification compliance. Further, the DART gage responses, combined with the finite element based nomographical solution scheme, can estimate the binder $G^*$ and $\delta$ satisfactorily. Both these findings further the notion that DART can be used for rapid QA testing of asphalt binders along the asphalt binder’s journey from a supplier to the job-site in a cost-effective and rapid manner.
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CHAPTER 1. INTRODUCTION

1.1 Use of Asphalt in Paving Applications

Abraham (1938) traces back the first known use of asphalt cement or binder for civil engineering applications to the Mohenjo-Daro civilization of 3000 B.C., where it was used as a water stop between brick walls. Paving applications of asphalt were also reported around the same period from the Middle East (Abraham 1938). However, it was not until 1858 that the first major modern application of asphalt for road use was recorded (Abraham 1938). This project was constructed on a small street close to the Champs-Elysees in Paris, France. In the United States, the first successful asphalt road projects were built between 1870-1873 and were located in Battery Park and on Fifth Avenue of New York City (Abraham 1938). This was followed by the construction of the famous Pennsylvania Avenue in Washington, DC in the year 1876 (Abraham 1938). Since then the use of asphalt for paving applications has seen a steady rise in the United States. According to the National Asphalt Pavement Association 2012 web statistics, it is estimated that about 500 to 550 million tons of asphalt is placed in the United States every year. This is a 500-fold increase over the estimated annual asphalt sales in 1915 when the sale of asphalt first crossed the one million ton mark (Krchma and Gagle 1974).

Most of the early asphalt used in road building in the United States came from natural sources such as lakebeds and rock deposits. For example, the asphalt used in the construction of Pennsylvania Avenue was obtained from the bottom of Pitch Lake on the island of Trinidad. Asphalt obtained by mining the bed of the Bermudez Lake in Venezuela, which came into use in a major way in 1901, is another example of a lake asphalt. Other natural sources of asphalt include gilsonite, wurzilite, and other similar vein asphalts which were mined like coal. However, at the turn of the 20th century, the growth of the automobile created a need for more paved surfaces. Simultaneously, a need was also created for roads that had tougher and more resistant surfaces than their “macadamized” counterparts. The asphalt supply from the natural sources could not meet these demands. Fortunately, concurrent to the demand for better road wearing surfaces was the demand for increased
gasoline production for the automobiles. This latter demand led to the rapid development of modern day paving asphalt, which is a by-product petroleum crude distillation process through which gasoline is manufactured. This form of asphalt, first produced at the turn of the 20th century, did not change greatly in composition until the 1980s when additives such as tire rubber, polymers, and other chemicals began to be added in order to improve the fatigue and low-temperature properties. What has changed in asphalt production over the years is the refining process, material handling and distribution, asphalt grade specification and acceptance testing.

1.2 Asphalt Binder Specification Testing Prior to Superpave

Simultaneous to the increase in the popularity of the asphalt binder were the efforts to study and characterize its physical and chemical properties. Because asphalt is a by-product of the petroleum refining process, it is material whose chemical composition is determined by the crude source as well as the targeted end-use application of the product, e.g., roofing applications, paving applications, etc. Each intended application of the asphalt by-product has some form of a performance specification which controls its production and hence its physical and chemical characteristics.

A significant portion of the innovation in asphalt binder specifications originated from the United States. The first specification for asphalt binders in the United States was written for the Trinidad lake asphalt and was based on simple tests such as visual appearance and solubility (Halstead et al., 1985). This was deemed adequate at the time because the biggest variant in the composition of naturally occurring asphalts, which could cause significant changes in the material’s behavior, is the amount of mineral deposits present. These minerals were found to be insoluble in common organic solvents.

With the introduction of petroleum asphalts around 1900, the sources available to supply asphalt binders for paving applications multiplied greatly. Significant advancements were also made in the production of the asphalt binders from the crude oil sources. The production of heavy crude oils, (as determined by their density) which are the best source for
paving asphalt, is on the rise. Fractional distillation is typically used to fractionate and separate the crude oil residuum which is then blended at the oil refineries to produce desired material characteristics such as viscosity, durability, adhesion, and cohesion. If the desired properties are unattainable from a single fraction, blending is done which combines two or more different fractional distillation by-products to obtain the target properties for the final asphalt binder product. Blending also involves adding asphalt modifiers and additives either at the refinery, terminal, or plant. A broad spectrum of asphalt modifiers and additives including antistripping agents, extenders, fibers, fillers, thermoplastics, polymers, and waxes have been used to modify the properties of the asphalt binder to produce a variety of hot mix asphalts (e.g., conventional, stone matrix, polymer modified, rubber modified) or warm mix asphalts.

As can be expected, asphalt binders manufactured from various sources vary in chemical and physical properties. Consequently there was a need to develop specification tests to control the quality of asphalt binders and to prevent the use of inferior materials. Asphalt researchers looked at a number of ways to test asphalt binders over the past several decades to identify appropriate specification parameters, construction and design parameters. A brief discussion of the evolution of the asphalt specification tests prior to the advent of the Superpave specification system is presented in the following paragraphs.

### 1.2.1 The Chew Test

The first recorded approach to determine whether an asphalt binder was suitable for a given construction project was to test it by chewing on a small sample of it (Roberts et al. 1996, Halstead et al. 1974). This test was primarily used between 1870s and early 1900s (Roberts et al. 1996, Halstead et al., 1974) and was discontinued subsequently owing to its unscientific, subjective and hazardous nature.
1.2.2 The Penetration Grading System

In 1888, H.C. Bowen of the Barber Asphalt Company invented the Bowen Penetration Machine, the forerunner to the modern day penetrometer. The equipment was refined by Dow (1903) and the New York Testing Laboratory to overcome some of the deficiencies in the original Penetration Machine. By 1910, the penetrometer became the principal means of measuring and controlling consistency of semi-solid asphalts. Concurrent to the development of the penetrometer were the inventions of many other pieces of equipment to test for physical and chemical properties of asphalt such as the flash point, ductility, solubility, specific gravity, softening point, and so on. By 1918, a formal penetration-based asphalt grading system was introduced by the Bureau of Public Roads which included most of the tests discussed above (Halstead, 1974; Roberts et al., 1996). This system was later adopted by the American Association of State Highway Officials (AASHO) and the American Society for Testing and Materials (ASTM) Committee D4 with some modifications, e.g., introduction of the “skip” grading system. The current ASTM standard for penetration-graded asphalts is specified in ASTM D946/ D946M - 09a. Five penetration grades are specified in the ASTM specification—40-50, 60-70, 85-100, 120-150, and 200-300. Each penetration unit equals one-tenth of a millimeter (0.1 mm) penetration achieved by a standard needle under standard test conditions in a given asphalt binder sample at 25°C (77°F). Higher penetration grades generally mean “softer” asphalts in terms of their moduli and vice versa.

1.2.3 The Viscosity Grading System

The next important change in the asphalt binder specifications took place in the early 1960s when AASHO and a number of States adopted a specification based on viscosity grading at 60°C (140°F) (Halstead et al., 1974; Roberts et al., 1996). One of the primary reasons for this shift was to move the specifications from being based on empirical units such as penetration to more fundamental measures of consistency such as viscosity. Drawbacks such as a very high and variable shear rate and inability to characterize temperature susceptibility with the penetration grading system also led to the development of the newer specifications. According to Schweyer (1974), although the viscosity grading of asphalts was finally
adopted as a standard in early 1970s, the migration toward this more fundamental measure of consistency was aided by gradual development of the viscometer since the 1870s.

The current viscosity-based specification, outlined in ASTM D3381/D3381M-12, is based on testing the original (unaged or tank) as well as rolling thin film oven (RTFO) aged asphalt binder at 60°C (140°F). The unaged specification is the most frequently used, however. Requirements for six different asphalt binder grades—AC-2.5, AC-5, AC-10, AC-20, AC-30, and AC-40—are provided in the specification. An asphalt binder grade AC-2.5 represents asphalt with a viscosity of 250 Poise at 60°C (140°F). The higher the asphalt grade the more viscous the asphalt binder and vice versa. In addition to meeting the requirements for the viscosity at 60°C (140°F), the asphalts must also satisfy the requirements for viscosity at 135°C (275°F), penetration at 25°C (77°F), flash point, solubility, ductility, and aged residue viscosity as laid out in ASTM D3381. The viscosity-based asphalt grading system was used from the 1970s to about the beginning of the 1990s without much alteration.

1.3 The Superpave Performance Grading System

1.3.1 The Superpave Performance Grade (PG) Binder Specification

In 1984, the Strategic Transportation Research Study identified asphalt as one of the six priority areas for research and development. Some the reasons for focusing research efforts in this area include (McGennis et al. 1995, Anderson et al. 1993, Kennedy et al. 1993):

- **Inadequate specifications**: The penetration and viscosity-based asphalt binder specifications in use at the time were not sufficient to properly describe the linear viscoelastic and failure properties of asphalt binder that are needed to relate asphalt binder properties to pavement performance. The existing specifications were particularly deficient in characterizing the temperature susceptibility of asphalt binder, particularly the low temperature behavior.
• **Premature pavement failures**: The inadequate specifications lead to several premature pavement failures. This created a need for a performance-based specification.

• **Inadequate research**: Although petroleum-based asphalt was in existence for over a hundred years prior to the initiation of the study, there has never been a large-scale research effort to study the fundamental physical and chemical properties that affect asphalt behavior.

• **Increasing importance of asphalt**: Approximately 15 billion dollars are spent annually on building asphalt roads. Asphalt concrete accounts for about 90 percent of paved roads in the United States.

• **Use of asphalt modifiers**: The usage of modifiers such as crumb-rubber and polymers created the need for an improved asphalt binder specification that can directly relate the impact of these modifiers on pavement performance.

The Strategic Highway Research Program (SHRP) was created in 1987 with a budget of $150 million, to undertake research in the areas of asphalt, concrete and structures, long-term pavement performance, pavement maintenance, work zone safety, and snow and ice control. The research on asphalt was conducted between 1987 and 1993 at an expense of $50 million under eight separate contracts. The main objective of the SHRP asphalt research was to improve pavement performance through an increased understanding of chemical and physical properties of asphalt binders and asphalt concretes. The asphalt binder research was expanded to encompass both modified and unmodified binders. The research results were required to be as practical as possible with the aim of developing specifications, tests, protocols, and equipment that will enable engineers to control the pavement performance as desired.

The main product of the SHRP research effort was the development of the Superpave asphalt performance grade (PG) binder specification with supporting test and testing protocols. The PG specification tests a given asphalt binder over the range of temperatures likely to occur at a project location and determines its susceptibility to develop the three primary binder-related modes of pavement distress—permanent deformation or rutting, fatigue cracking, and low-
temperature or thermal cracking. The asphalt is tested in its original, short-term aged (cause by binder hardening during plant mixing and laydown) and long-term aged (caused by binder hardening due to oxidation of asphalt binder from prolonged exposure to the elements) forms. Test parameters from the testing were shown to correlate with the various modes of pavement distress in the SHRP program.

The PG binder specification that came out of SHRP was primarily based on the stiffness of unmodified asphalt binders in both original and aged conditions. The unique aspect of the specification is that the desired stiffness of the binder is a constant—only the temperature for each test is varied to maintain the stiffness value at the preset level. All asphalt binders, regardless of their source, are expected to produce the same stiffness level to satisfy performance at the expected temperatures for a given location. The design temperatures are obtained based on climatic data for the given location.

The performance-based specification for one high temperature asphalt binder grade is described in Figure 1 as an example. An asphalt binder assigned a performance grade of PG 64-22 from Figure 1 would meet the specification for a design high pavement temperature up to 64°C (147°F) and a design low temperature warmer than –22°C (-8°F). The PG-based specification utilizes the following properties to characterize the binder:

- Original (unaged) binder tests:
  - Specific gravity.
  - Flash point temperature.
  - Rotational viscosity.
  - Complex shear modulus, G*, and phase angle, δ, at the highest pavement in-service temperature the binder is expected to perform under.
- RTFO aged binder tests (representing the aging an asphalt binder undergoes during asphalt mixture production and placement):
  - G* and δ at the highest in-service pavement temperature.
- Pressure aging vessel (PAV) aged asphalt binder testing (representing the long-term aging of the asphalt binder in service):
- $G^*$ and $\delta$ at the estimated intermediate in-service pavement temperature the binder is expected to perform under.
- Creep stiffness ($S$) and rate of creep ($m$) at the lowest pavement temperature.
- Failure strain in direct tension (DT) at the lowest pavement temperature.

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<td>Direct Tension, AASHTO T314 Failure Strain, min 1.0%, Test Temperature, $C$</td>
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Figure 1. Sample Superpave specification for asphalt binder testing (from Table 1 of M 320-10, Performance-Graded Asphalt Binder, from Standard Specifications for Transportation Materials and Methods of Sampling and Testing, 2012, by the American Association of State Highway and Transportation Officials, Washington, D.C. Used by permission.).
1.3.2 **PG Binder Test Equipment**

As indicated in Figure 1, the PG binder specification uses the following pieces of equipment to collect the required test parameters to assess specification compliance:

- **The Rolling Thin Film Oven**: The RTFO is employed to simulate short-term aging of asphalt.
- **The Pressure Aging Vessel**: The PAV is employed to simulate long-term aging of asphalt.
- **The Rotational Viscometer (RV)**: The rotational viscometer is used to the original asphalt binder at 135°C (275°F) to collect viscosity information. The purpose of this test is to ensure that the binder is pumpable.
- **The Dynamic Shear Rheometer (DSR)**: The DSR, which is essentially a parallel plate device, tests the original asphalt as well as the RTFO and PAV residues. The test on the original and RTFO is conducted at the anticipated high pavement temperature used in the design and the test on the PAV residue is conducted at the estimated intermediate pavement temperature. Collectively, the DSR tests ensure resistance to permanent deformation and fatigue cracking. The DSR tests the asphalt specimen in dynamic shear mode at 10 rad/s and can be performed in the constant stress or constant strain mode. The material parameters derived from the test are G*, storage modulus (G’), loss modulus (G”) and the phase angle δ of the asphalt binder. The DSR is generally required to operate in a stiffness range of 0.145 psi (1kPa) to 725 psi (5 MPa) for the Superpave PG binder testing.
- **The Bending Beam Rheometer (BBR)**: The BBR, which is basically used to measure the low-temperature creep stiffness of asphalt binders in flexure, is used to test the PAV residue at the lowest pavement design temperatures. The primary parameters of interest from the BBR are the creep stiffness as a function of loading time, S(t), and the creep rate of the binder (m) at 60 seconds. The BBR is useful for measuring moduli in the range of 4350 psi (30 MPa) to 435 ksi (3 GPa) where the DSR is considered inadequate for rheological testing.
• **The Direct Tension (DT) Device**: The DT device is also used on PAV residue to determine the failure strain at the lowest design temperature.

### 1.3.3 Enhancements to the PG Binder Specification, Test Equipment and Standard Practices

The current governing standard for PG binder specification is AASHTO M320. It can be used to either classify a binder or to verify specification compliance. The procedure for classification and verification is outlined in AASHTO R 29. The current version of the AASHTO M320 specification (2012) has significantly evolved from the original version developed at the conclusion of the SHRP program. Some of the salient changes include the following:

- Refinement of the DT test device to address issues related to testing and equipment related issues (Dongre et al. 1997).
- Development of a new standard practice to interpret the results of the BBR and DT test to determine low temperature cracking performance of the asphalt binder (AASHTO R 49). AASHTO M 320-10 Table 2 incorporates the R 49 practice for determining the critical low cracking temperature using a combination of AASHTO T 313 and AASHTO T 314 test results.
- Development of newer standards to facilitate the specification of polymer modified binders. As stated earlier, the original PG binder specification from SHRP was based on unmodified binders. With the increased use of polymer modifiers beginning in the late 1980s, research was done to refine the specification and testing standards to encompass these materials. The primary concern with AASHTO M320 Table 1 was that the $G*/\sin \delta$ test parameter does not adequately characterize the ability of polymer modified binders to resist rutting. The Multi-Stress Creep and Recovery (MSCR) test was developed to replace the existing RTFO-DSR high temperature requirement. The parameter, $J_{nr}$ (non-recoverable creep compliance), from this test has been shown to be more discriminating in identifying the rutting potential of both modified and neat binders (FHWA 2011). AASHTO TP70 and AASHTO MP19 are the test and
specification standards of the MSCR test, respectively. Table 3 in the AASHTO M320 specification incorporates TP 70 for determining $J_{nr}$.

Much of the post-SHRP Superpave binder related work has greatly advanced the ability of the current standards to specify and test for specification compliance of modified and unmodified asphalt binders. Work is still underway to improve some aspects of the low temperature characterization of asphalt binders to further upgrade the current standards.

The Superpave PG specification for asphalt binders represents a significant step forward in asphalt technology. In addition to the continued research and development activity to strengthen the specification, post-SHRP implementation activities lead by the Federal Highway Administration (FHWA) and state DOTs in the form of pooled fund equipment purchase programs, software/tool development to assist with the selection of an appropriate PG graded binder for a given project location, training courses and mobile laboratories to educate engineers, and regional Superpave centers to provide technical assistance to practitioners has greatly contributed to the widespread adoption of the PG binder specification in the United States. Several DSR, BBR and DT devices that meet the strict testing requirements of the AASHTO standards are commercially available today for binder grading or specification compliance testing purposes.

1.3.4 Quality Assurance of Performance Graded Asphalt Binders Delivered to the Job

The Superpave PG binder specification and the attendant test equipment, standards, and standard practice specification represent the state-of-the-art in asphalt binder characterization in the laboratory. However, since the specification covers a number of test parameters measured over a multiple temperatures and binder aging conditions, compliance verification is not an easy task. Martin et al. (2003) note that a number of factors may affect the test parameters between production and use during construction. These factors are shown in Table 1. In Figure 2, Martin et al. (2003) indicate the potential locations along the asphalt supply chain where binders can be sampled and tested to ensure their quality. A robust QA
program must sample and test the asphalt binder at various points in time along its journey from the refinery to the job-site.

![Diagram of asphalt binder production and testing process]

Figure 2. Potential sampling locations for QA testing of asphalt binders at various stages of asphalt production, transport and job-site delivery (redrawn from Martin et al. 2003).

Table 1. Factors that may affect binder properties (from Martin et al. 2003).

<table>
<thead>
<tr>
<th>Category</th>
<th>Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplier Location</td>
<td>Storage temperature (overheating)</td>
</tr>
<tr>
<td></td>
<td>Blending</td>
</tr>
<tr>
<td></td>
<td>Changing crude source</td>
</tr>
<tr>
<td></td>
<td>Refinery process (temperature or pressure)</td>
</tr>
<tr>
<td></td>
<td>Contamination in tanks</td>
</tr>
<tr>
<td>Transportation</td>
<td>Contamination in tanks</td>
</tr>
<tr>
<td></td>
<td>Overheating</td>
</tr>
<tr>
<td>Contractor Location</td>
<td>Storage time</td>
</tr>
<tr>
<td></td>
<td>Storage temperature (overheating)</td>
</tr>
<tr>
<td></td>
<td>Contamination/Mixing different binders</td>
</tr>
<tr>
<td></td>
<td>Separation</td>
</tr>
<tr>
<td></td>
<td>Dilution</td>
</tr>
<tr>
<td></td>
<td>Presence of modifier</td>
</tr>
</tbody>
</table>
While the need for field sampling and testing is clear, the following issues arise when contemplating the use of the Superpave binder test equipment in the field for QA purposes:

- The equipment is ideal for use in a controlled laboratory environment and cannot be easily taken to the field (contractor plant) for on-site investigations. This is by far the most significant drawback of the existing binder testing equipment from a field QA standpoint.

- The use of the equipment requires significant operator skill to minimize the potential for large errors. For example, sample trimming, calibration, and gap setting need to be done with great care while using the DSR to reduce measurement errors. It is not easy to maintain and staff qualified field technicians at the job-site. For this reason far less sampling and testing of asphalt binders for specification compliance than necessary for a robust QA program is currently performed.

- The cost of acquiring a full set of binder testing equipment and maintaining qualified staff on-hand is relatively high and requires a significant investment from contractors and owner agencies from a QA standpoint.

- Although the Superpave binder specification is intended for use with modified as well as original asphalt, the sample geometry used in the original DSR testing protocol may preclude some crumb rubber modified binders from being tested if the size of the rubber particles exceeds or approaches the gap-setting requirements between the parallel plates. In order to accommodate these materials, the original equipment setting may have to be changes as was done by some researchers (Hanson and Duncan 1995, Baumgardner and D’Angelo 2012). Note that the AASHTO M320-12 specification only covers non-particulate binders.

- The low-temperature evaluation of the asphalt binders is done using the BBR and the DT devices. However, it is preferable to use the same device to perform testing over the full range of AASHTO M320 temperatures providing the same rheological parameters.
Compliance verification along the supply chain of the asphalt (from the refinery to the job-site) is consequently a more labor-intensive, time consuming, specialized, and expensive process. The aforementioned issues have somewhat limited the ability of owner agencies to verify and put in place statistically-based QA programs to monitor binder quality and to take corrective action or define pay adjustments.

Most current state DOT asphalt binder QA programs are based on the AASHTO procedure PP26 titled “Standard Practice for Certifying Suppliers of Performance Graded Asphalt.” Introduced in 1997, this standard aims to expedite construction by pre-certifying suppliers if they meet their responsibilities towards assuring PG grade specification compliance. According to Martin et al. (2003), state DOTs may require sampling at the production source (supplier sample) during construction (field sample), or both. AASHTO PP26 provides guidance for minimum contractor quality control (QC) plan components (transport inspection guidance, test frequencies, laboratory accreditation requirements) and a standard form for reporting data (Martin et al. 2003). Agency responsibilities outlined in AASHTO PP26 include acceptance of the QC plan, administration of a supplier certification program, and inspection of supplier facilities (Martin et al. 2003). The standard also describes provisions for split sample and QA sampling and testing.

In terms of testing for compliance verification many owner agencies do not perform the full battery of tests required by AASHTO M320. Because the complexity, cost, and resource intensive nature of the testing involved with the PG binder, they have adopted a simpler testing regime consisting of testing for either the DSR-original and/or DSR-RTFO at the high temperature of the PG grade (Epps et al. 2001) based on supplier sourced samples. Some agencies, with limited field laboratory capabilities, do not perform any testing at all. One agency (Maryland) performs “fingerprint” testing using surrogate and easier test standards such as the Brookfield rotational viscosity (AASHTO T321). The risks associated with accepting asphalt binders delivered to the job-site on the basis of supplier pre-certification or limited to no testing are large and unacceptable and could lead to premature pavement failures as noted by Texas DOT (2011) one of their projects (reported in Martin et al. 2003).
1.3.5 Need for Rapid Field QA Test Devices

The need for methods to rapidly and cost-effectively ensure that the asphalt being delivered to the job-site is compliant with the intended specification has been in existence for almost as long as asphalt specifications have existed. This need has been a source for innovative testing methods over the years. For example, the “chew” test was used as an expedient surrogate check of asphalt consistency even when penetration testing was considered the more scientific method.

A relevant research effort to the Superpave PG binder specification employs a flow measurement device, borrowed from the polymer industry, to rapidly test asphalt’s material volumetric flow rate (MVR) in the field. The MVR is then used as a test parameter to ensure batch-to-batch invariance for QC/QA purposes (Shenoy 2000, Shenoy 2001)—like a “fingerprint” test. The method is only intended to test liquid asphalt and consequently is only able to verify the high temperature grade of the asphalt binders. Further, the material parameters deduced from this test are related to the PG binder specification properties by statistical correlations only. Nevertheless, this research further highlights the need for a supplemental device to test for asphalt specification parameters in a rapid manner. Such a device can be used for both QC and acceptance of the asphalt binder under an agency prescribed QA program.

1.4 The Proposed New Asphalt Test Device

In the 1970s Briar and Bills (1972) and Briar et al. (1976) investigated the use of a piezoelectric (PZT) transducer, known as the duomorph, as a permanently embedded sensor for long-term surveillance of the structural integrity of solid rocket propellant fuel. The studies concluded that the duomorph is a feasible tool to determine the dynamic mechanical properties of the viscoelastic medium such as complex modulus and phase angle. Encouraged by this research, Boggess (1980) extended this concept, with considerable success, to determining complex modulus of asphalt concrete. The duomorph was also found feasible to rapidly determine the mechanical properties of marine sediments (Breeding and Lavoie 1988, Lavoie et al. 1996).
These studies indicate that the duomorph has the potential to function as a low-cost, durable, and portable supplemental testing device to the DSR for QA testing of asphalt binders both in terms of stress/strain and frequency levels employed thereby removing any misgivings of it being an surrogate test procedure producing data that violates the assumptions of the specification. Further, the duomorph also has the potential to function over the entire temperature range of interest to Superpave binder grading, extending to the lowest pavement temperatures expected and still providing the same rheological data, not an adjusted value. In addition, the duomorph is an implantable device capable of performing long-term viscoelastic monitoring to detect steric or oxidative hardening due to storage at elevated temperatures. The past successes of the duomorph and its theoretical potential to perform asphalt binder testing consistent with the existing Superpave specification contributed significantly in framing the objectives of this study and formulating the various work items.

1.5 Research Objectives and Scope

The primary objective of this research, funded under two NCHRP-IDEA contracts (NCHRP-94-ID017 and 20-30/NCHRP-41), was to fabricate a duomorph-based testing system given the name – Duomorph Asphalt Rheology Tester (DART) – and to evaluate its feasibility to perform Superpave PG asphalt binder testing in a consistent and rapid manner for specification compliance verification purposes. This was accomplished through a logical “redevelopment” of the duomorph technology with suitable adjustments, refinements, and advancements to specifically fine tune it to asphalt binder testing. This research is aimed at enhancing the implementation of the Superpave binder testing through the production of a viable piece of equipment to perform field QA testing of asphalt binders.

In order to achieve the stated objectives, the following tasks were undertaken:

- **Construction of the DART System**: The work items under this task included upgrading the current state-of-the-art in duomorph technology through piezoelectric materials research, electronic subsystem improvements, optimization
of transducer assembly and sensor dimensional design for operation in asphalt, and coding software to perform desired sensor actuation and data collection.

- **Shakedown Testing**: In this task the applicability of the DART system to perform asphalt binder testing, its durability and potential accuracy were assessed. Based on this testing, a standardized DART system to perform asphalt binder testing was developed.

- **Theoretical Analysis of the DART Sensor**: In this task a finite element model was created to simulate the behavior of the DART’s duomorph gage when it is operating in air (unconstrained response analysis) as well as when it is embedded in an asphalt medium (constrained response analysis). This improved analytical framework was then validated using laboratory measured DART gage responses.

- **Data Reduction and Analysis**: The validated finite element model was then used to develop a data reduction scheme to obtain asphalt binder $G^*$ and $\delta$ from raw DART gage responses. The model was also used to theoretically investigate the binder stiffness range over which satisfactory results could be expected from the DART system.

- **Validation Testing**: Analysis was conducted to assess the feasibility of the DART to act as (1) a “fingerprinting” device to rapidly and consistently characterize the unique signature of asphalt binders over a range of test temperatures and frequencies and (2) a device that is capable of estimating the high and intermediate temperature DSR parameters of the AASHTO M320 specification—$G^*$ and $\delta$.

### 1.6 Organization of the Dissertation

This dissertation describes some of the development, testing, and analysis performed to develop the DART system to test asphalt binders. It is organized as follows:

- Chapter 1 provides background information including historical and current approaches used to specify and test asphalt binders. The chapter advances arguments of why better QA monitoring systems are needed to test the quality of
asphalt binders in the field and provides a brief description of the DART system and its origins.

- Chapter 2 presents some background information on piezoelectric transducers with focused discussion on the duomorph. A discussion of successful applications of the duomorph technology to characterize mechanical properties of materials is also presented. The chapter concludes with a presentation of the apparent deficiencies of the existing duomorph technology and the need to further adapt and develop it to characterize asphalt binders.

- In Chapter 3, efforts made to develop the DART system are summarized along with a discussion on the durability, ruggedness, and accuracy of the test equipment. The ability of the DART to “fingerprint” asphalt binders and its limitations are also discussed. Optimal DART gage dimensions and equipment needed to operate it to either “fingerprint” or characterize G* and δ of asphalt binders are also presented in this chapter.

- In Chapter 4, a finite element (FE) model developed to analytically compute the DART responses when operated in air or after embedment in an asphalt binder is presented along with a discussion on why this model was developed and how it differs from existing analytical schemes. The DART FEM model is validated using laboratory data in this chapter.

- Chapter 5 discusses a parametric study conducted on the basis of the FE model to develop a nomograph-based data reduction scheme to estimate asphalt binder G* and δ from DART measurements. This data reduction scheme is compared and contrasted with previous analytical schemes to understand the differences and verify the reasonableness of the observed differences. The chapter concludes with a limited validation study conducted using the FE-based data reduction scheme to estimate the G* and δ of some asphalt binders.

- Finally, Chapter 6 presents the conclusions from the study and identifies areas for future research.
CHAPTER 2. THE DUOMORPH

The duomorph is a central component of the DART system developed in this research. It is a sandwich assembly of a circular steel disc or shim placed concentrically between two piezoelectric circular discs. The operational characteristics of the duomorph are heavily influenced by the geometric properties of the individual components of the duomorph as well as their materials properties, particularly the piezoelectric discs. In this chapter, a general overview of the history of the piezoelectricity, the evolution piezoelectric materials, and the theory of piezoelectricity are discussed initially. Next, the operating principle of the duomorph, its past applications, and its application for asphalt binder testing are discussed. The information presented in this chapter will aid in understanding some of the choices made in this dissertation regarding the duomorph materials selected, gage dimensions and the DART electronic sub-assembly.

Throughout this chapter and the remainder of this report, the terms duomorph, duomorph gage or sensor, and DART gage or sensor will be used interchangeably. Additionally, although the duomorph is referred to in the industry today as a bimorph or a piezoelectric bender, the former term is retained in the interest of continuity with previous research in this application area. Further, even though the duomorph can function both as an actuator or a motor (converts electrical energy to mechanical energy) and a sensor or generator (converts mechanical energy into electrical energy), in this research, it has been primarily used as a sensor. Therefore, phrases such as the “duomorph sensor” or the “DART sensor” are appropriate.

2.1 Definition, History, and Applications of Piezoelectricity

Several textbooks and journal articles discussing piezoelectricity in great depth are available in literature. Some seminal books and articles dealing with the subject include Cady (1964), Jaffe et al. (1971), Mason (1981), Gagnepain et al. (1982), and Ikeda (1990). In addition, several online publications by piezoelectric material manufacturers (such as Morgan Electroceramics, Inc., Piezo Systems, Inc., and others) also discuss the topic in great detail.
Much of the discussion presented in the following sections is excerpted from some of these publications to present a proper introduction and background to the discussion intended in this Chapter.

### 2.1.1 Definition of Piezoelectricity

Piezoelectricity is a coupling between the electrical and mechanical behavior of a material. In the simplest terms, when a piezoelectric material is squeezed, electrical charge collects on its surface. Conversely, when a piezoelectric material is subject to a voltage drop, it deforms mechanically. These effects are appropriately termed as the “direct” and “converse” effects, respectively.

A more rigorous definition of piezoelectricity is obtained from crystallographic and molecular considerations. Solid matter consists of positively and negatively charged particles disposed in space in such a way that they are in exact balance in an uncharged body. The development of electric surface charges by mechanical deformation is therefore not unexpected. However, considerations of crystal symmetry limit the conditions under which such charges appear (Morgan Electroceramics Website TP 238 n.d.). On a nanoscopic scale, piezoelectricity results from a nonuniform charge distribution within a crystal’s unit cells, i.e., lack of a center of symmetry. When such a crystal is mechanically deformed, the positive and negative charge centers displace by differing amounts. So while the overall crystal remains electrically neutral, the difference in charge center displacements results in an electrical polarization within the crystal. Crystallographic research studies note that, twenty-one of the 32 crystal classes (each representing a type of unit cell) lack a center of symmetry, and crystals in all but one of these classes can exhibit piezoelectricity (Jaffe et al. 1981, Morgan Electroceramics Website TP 217 n.d.).

Figure 3 pictorially depicts the direct and converse piezoelectric effects. The arrows in the figures correspond to the alignment of micro-dipoles within the piezoelectric material. Dipoles result from a difference in the average location of the positive and negative charges in a unit cell. Uniform alignment of the dipoles, as suggested in the figure, is necessary for
the piezoelectric effect to occur. This requirement is in addition to the material having a chemical composition conducive for exhibiting piezoelectric behavior. The uniform alignment of the micro-dipoles could be either naturally occurring or induced with the help of a strong electrical field as is done in the case of piezoceramic materials.

![Piezoelectric element at rest.](image)

(a) Piezoelectric element at rest.

![Direct effect](image)

(b) Direct effect

![Converse effect](image)

(c) Converse effect

Figure 3. Illustration of the piezoelectric effect.

### 2.1.2 History of Piezoelectricity and Piezoelectric Applications

Pierre and Jacques Curie first discovered the piezoelectric phenomenon in 1880 as a result of extensive theoretical and experimental studies of symmetry of crystalline matter. Through their work, they conclusively established a connection between surface charges appearing on specially prepared crystals (tourmaline, quartz, topaz, cane sugar, and Rochelle salt) and the mechanical stresses applied to them, i.e., they discovered the “direct” piezoelectric effect. Lippmann in 1881 deduced, through the application of fundamental thermodynamics, that crystals exhibiting the direct piezoelectric effect also exhibit the converse effect. The Curie brothers confirmed this in 1882 and then continued on to obtain quantitative proof of the complete reversibility of electro-elasto-mechanical deformations in piezoelectric crystals.

According to Piezosystems Inc. (Piezo Systems Inc. n.d.) the next two decades after the discovery of the piezoelectric effect lead to the development of the core of piezoelectric application science. Some important contributions during this period included the
development of a framework, which completely defined the 20 natural crystal classes in which piezoelectric effects occur and a thermodynamics-based theoretical analysis of crystal solids. By the end of this period it was recognized that the science of piezoelectricity was extremely complex and required the application of rigorous mathematical approaches such as tensorial analysis just to define relevant measurable quantities.

According to Morgan Electroceramics Inc. (TP 238 n.d.) The first important engineering application of piezoelectricity was an underwater ultrasonic source developed to detect submarines in 1916 by Paul Langevin. This device comprised of a quartz element sandwiched between steel plates. The types of materials available during these early developmental stages of piezoelectric technology were limited to single crystal materials such as quartz and Rochelle salt. This limited the efficacy of the applications of the piezoelectric phenomenon since these materials were not adaptable to all types of situations. About 1940, a major breakthrough was obtained in the development of man-made piezoelectric materials through the discovery of the ferroelectric nature of oxide ceramics such as barium titanate by Arthur von Hippel and his co-workers at the Massachusetts Institute of Technology. Characteristic of ferroelectrics is the existence of “domains”, i.e., regions within each crystal that have a spontaneous electric polarization. It was discovered that when these materials were treated in a strong electric field opposite in sense to the existing crystal dipoles, the direction of polarity in the crystallites is reversed, thereby, rendering the material strongly piezoelectric. The property that facilitates this dipole reversing is termed ferroelectricity. This discovery opened the way for the development of piezoelectric elements comparable with the naturally occurring Rochelle salt in sensitivity and quartz in chemical stability. Further, advancements in ceramic preparation methods made possible shapes and sizes that were unattainable with single crystals.

In 1947, the first piezoelectric transducer employing the barium titanate ceramics was developed. This class of materials has been gradually replaced since 1957 by lead zirconate-titanate solid-solution ceramics, commercially referred to by the acronym PZT (taken after usage by Vernitron Inc.), offering higher piezoelectric coupling, wider operating temperatures, and a choice of useful variations in engineering parameters (Jaffe and
Berlincourt 1965). Today, piezoceramics are the most widely used piezoelectric materials available and are used in the present research as well. The applications include sonar, sonobuoys, microphones, accelerometers, bender element actuators, signal filters, ignition systems, buzzers, clocks, and so on.

2.2 Piezoceramic Materials – Preparation and Types

Piezoelectric ceramic materials are manufactured using processes generally applied in preparing electric insulator ceramics but with closer control of impurities. A solid state reaction of several oxides or carbonates is followed by high temperature firing involving crystal grain growth. Subsequently, the ceramic bodies are given closely adhering electrodes, usually in the form of fired-on silver preparation. These electroded masses are then subject to a high direct-current voltage, typically 50,000 volts/inch, for periods as long as 1 hour at temperatures close to the Curie temperature1 for the material. This process renders the ceramics polar; the direction of polarity being parallel to the direction of polarization within the ceramic (Morgan Electro Ceramics TP-238 n.d.). An electroded ceramic body showing the direction of the polar axis is shown in Figure 4.

![Figure 4. Piezoelectric element showing electrodes and axes orientation.](image)

The dielectric constant of ferroelectric materials is typically very high, but in the vicinity of the Curie temperature it reaches its peak. This temperature therefore acts as an operating

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1 A characteristic temperature in most ferroelectrics above which the domain structure disappears and the piezoelectric effect is lost.
constraint and also serves as a reference temperature for preferentially poling the piezoceramics.

Significant advancements have been made in recent times that have resulted in manufacturing of piezoceramics to tight material and geometric property tolerances at every step of the process including raw material processing, sintering, grinding, polishing, cutting, electroding, and poling. Besides, by varying the chemical composition of the parent materials, the properties of the piezoceramics can be optimized to cater to a wide application market. As stated earlier, the PZT solid solutions with approximately equal molar concentrations of titanium and zirconium, are the most widely used piezoceramics today. Many commercial sources supply piezoceramic materials, each source using slightly different techniques of crystal growth, electroding, bonding, and so on. However, regardless of the source, the piezoceramic materials can be broadly classified as “hard” or high power materials, “soft” or high sensitivity materials. A wide range of custom materials exhibiting intermediate properties are also widely available. Obviously, the nature of the application dictates the type of piezoelectric materials to be employed. In addition, factors such as time and temperature stability, maximum operating temperature and voltage, magnitudes of expected mechanical or electrical responses, size and shape limitations and other similar considerations can also dictate the materials selection.

Within the PZT class of materials, the following specific classifications are most prevalent: PZT-2, PZT-4, PZT-5A, PZT-5H, PZT-6, and PZT-8. The special characteristics of these materials are qualitatively highlighted in the following paragraph (Morgan Electroceramics TP-226 n.d.):

- **PZT-2**—May be used for requirements of low dielectric constant but is otherwise inferior, in nearly all respects, to PZT-4 and PZT-5A.
- **PZT-4**—Recommended for high power acoustic radiating transducers because of its high resistance to depolarization and low dielectric losses under high electric drive or mechanical stress. This high resistance to depolarization under high mechanical
stress makes it an ideal material for deep submersion acoustic transducers and as the active element in electrical power generating systems.

- **PZT-5A**—Recommended for hydrophones or instrument applications because of its high resistivity at elevated temperatures, high sensitivity, and high time stability.

- **PZT-5H**—This material has greater sensitivity and permittivity than PZT-5A, and is similar to PZT-5A in most other respects. However, it has a markedly lower Curie point, which limits the working temperature range and leads to a lower temperature stability.

- **PZT-8**—This material is similar to PZT-4 but has even lower dielectric and mechanical losses under high electrical drive. Recommended for application requiring high power handling capability than is suitable for PZT-4.

Qualitatively, PZT-2, PZT-4, and PZT-8 qualify as “hard” ceramics and PZT-5A and PZT-5H qualify as “soft” ceramics.

### 2.3 Characterization of Piezoelectric Materials and Relations of Piezoelectricity

#### 2.3.1 Piezoelectric Properties

Some of the key properties of interest for piezoelectric materials include:

- Electromechanical coupling, k.
- Dielectric constants.
- The d constant.
- The g constant.
- Young’s modulus and Poisson’s ratio.

These properties are explained briefly in the following paragraphs.
2.3.1.1 Electromechanical Coupling, $k$

The ability of a piezoelectric material to convert mechanical energy into electrical energy, and vice versa, is expressed as its electromechanical coupling coefficient, $k$ (Shields, 1966). It is a direct measure of the strength of the electromechanical effect. The electromechanical coupling coefficient is dimensionless. The following equations express $k$ mathematically:

$$k^2 = \frac{\text{mechanical energy converted to electrical energy}}{\text{input mechanical energy}} \quad \text{(direct effect)} \quad \text{Eq. 1(a)}$$

or conversely,

$$k^2 = \frac{\text{electrical energy converted to mechanical energy}}{\text{input electrical energy}} \quad \text{(converse effect)} \quad \text{Eq. 1(b)}$$

The value of the electromechanical coupling factor depends on the appropriate mechanical or electrical boundary conditions (Jaffe and Berlincourt 1965), i.e., free versus clamped or short- versus open-circuited.

The values specified for coupling coefficients $k$ are double subscripted, i.e., expressed as $k_{ij}$. The first subscript denotes the axis across which the electrodes are placed and the second denotes the axis along which the mechanical forces are considered. The position of the electrodes are specified by subscripts 1, 2, or 3, each representing the three major axes X, Y, and Z, respectively. Figure 4 depicts an arbitrarily defined coordinate system identifying the major axes 1, 2, and 3 (similar to X, Y, and Z of the classical right hand orthogonal axial set) for a piezoceramic body. This coordinate system will be used throughout this document. If the number 3 appears in the subscript, it is understood that the electrodes have been placed in a position perpendicular to the Z-axis. The order of the subscripts is maintained regardless of whether the stimulation is mechanical or electrical; and more importantly; the numerical value of $k$ is the same in either case. For example, $k_{33}$ is appropriate for a long thin bar, electroded on the ends, and polarized along the length and vibrating in a simple length expansion contraction.
In disc-shaped ceramics with electroded surfaces, such as those considered in this research, an electrical field applied in the 3-direction results in a mechanical response in the 1 and 2 directions simultaneously. This mode of operation is called the radial or planar mode and its coupling coefficient is denoted $k_p$. Typical $k_p$ values range from 0.35 to 0.70; the higher values obviously signifying a higher piezoelectric effect. Typical values of $k_p$ for three standard piezoceramic elements are noted below as a comparison (Morgan Electroceramics T-226 n.d.):

- PZT-4 – 0.58.
- PZT-5A – 0.60.
- PZT-5H – 0.65.

2.3.1.2 Dielectric Constants
The dielectric constant, $K$, is a measure of the amount of electrical charge a piezoelectric element can retain compared to the charge that would be stored by electrodes of the same area and separated by air as the dielectric (basically the same as a capacitor), i.e., it is the ratio of permittivity ($\varepsilon$) of the material to the permittivity of free space ($\varepsilon_0$). The dielectric constant is higher if the crystal is completely free to move; it is lower when the crystal is totally clamped. Two factors are generally included when specifying the dielectric constant of a given piezoelectric element – mechanical condition (free vs. clamped) and the relative position of the electrodes with regard to the three major crystal axes (Shields 1964). The dielectric constant is dimensionless.

The mechanical condition is specified using a superscript T (for an unrestrained condition) or S (for a completely restrained condition). The mechanical condition of the piezoelectric element is generally included when specifying its dielectric constant. For example, a piezoelectric element with a dielectric constant of $K^T_3$ indicates that it has zero mechanical constraint or stress applied to it and its electrodes are placed perpendicular to the Z axis. Typical values of $K^T_3$ for three standard piezoceramic elements are noted below as a comparison (Morgan Electroceramics T-226 n.d.):
The remarkable dielectric constants of the PZT-5H are to be noted.

2.3.1.3 The d Constant

The d constant also termed as “strain constant” relates the mechanical strain produced by an applied electric field. Conversely, it also relates the electrical charge collected per unit area of electrode to the mechanical stress applied. It is therefore given in units of meter/Volt (m/V) or Coloumb/Newton (C/N). These constants are directly applicable to bodies (such as the DART) which vibrating under laterally unrestrained conditions at frequencies at or below the fundamental resonance of the body (determined by its longest dimension) (Jaffe and Berlincourt 1965).

The d constants are expressed in tensorial notation (e.g., $d_{ij}$). The first subscript is the electrical direction and the second the mechanical direction. As in the case of the electromechanical coupling constant $k$, the subscripts 1, 2, and 3 refer to the X, Y, and Z axes. Shear stress or strain around the X axis is indicated by a subscript 4, around the Y axis by 5, and around the Z axis by 6.

For example, $d_{31}$ denotes the strain developed in the X direction to value of the electrical field applied in the Z direction. It also indicates the ratio of electrical charge per unit area of electrodes that are perpendicular to the Z axis to the stress applied to the X axis of the element. Typical values of $d_{31}$ for three standard piezoceramic elements are noted below as a comparison (Morgan Electroceramics T-226 n.d.):

- PZT-4 – -123.
- PZT-5A – -171.
- PZT-5H – -274.
2.3.1.4  The g Constant

The g constant of a piezoelectric material, also termed “voltage constant,” is obtained by dividing the d constant by the appropriate permittivity. It applies when the electrical displacement is taken as an independent variable. The g constant indicates the ratio of electric field generated along a given axis to the stress applied along (or around) a specific axis. It also denotes the ratio of strain generated along a given axis to the electric charge per unit area of electrodes perpendicular to a specific axis. The units of g are Vm/N or m²/C.

The g constant is also represented in the tensorial notation analogous to the d constant. Typical values of g₃₁ for three standard piezoceramic elements are noted below as a comparison (Morgan Electroceramics T-226 n.d.):

- PZT-5H – -9.11.

The g constants do not vary greatly from one piezocrystal to another when compared to the d constants and also do not show extreme temperature dependence as exhibited by the latter constants (Jaffe and Berlincourt 1965).

2.3.1.5  Elastic Compliance, Moduli, and Poisson’s Ratios

The compliance (s), modulus (e), and Poisson’s ratio (v) terms describe the mechanical deformation characteristics of piezoelectric materials and are similar to those for other materials. Compliance is more applicable when dealing with laterally unrestrained bodies a condition fulfilled when bodies are operating at or below their respective fundamental resonant frequencies and modulus values are applicable when dealing with laterally restrained bodies.
2.3.1.6 Other Miscellaneous Properties

Several other properties significantly influence the behavior. These need to be fully considered during the selection of a piezoelectric material for either a sensor or an actuator application. Some of these properties include:

- Piezoelectric stress constants (e) – relate the electrical charge collected per unit area of electrode to the mechanical strain applied or, conversely, relate the mechanical stress produced by an applied electrical field. They are expressed in units of C/m² or N/Vm. These constants are applicable more for high frequency applications or laterally restrained bodies.
- The h constants – obtained by dividing the e constants by the appropriate permittivity value. They are expressed in units of V/m or N/C.
- Density – denote the ratio of mass to volume in the material.
- Dissipation factor – a measure of dielectric losses in the material.
- Mechanical Q_m – ratio of reactance to resistance in the equivalent series circuit representing the resonant system.
- Curie temperature – representing the temperature where the crystal structure change from nonsymmetrical (piezoelectric) to symmetrical (non-piezoelectric). This value defines the working temperature range.
- Aging rate – this is the tendency of the piezoelectric material to revert back to its multi-polar state prior to polarization. Aging data are listed by change per decade of time. These rates tend to be linear per log of time, however, there are significant variations from this trend (Morgan Electroceramics TP-226 n.d.).

2.3.2 Effects of Temperature of Properties

Several piezoelectric and electrical properties, namely, the electromechanical coupling constants, stress and strain constants, dielectric constants, etc., vary with temperature. This poses a unique concern when the operating test temperatures vary as they do in asphalt binder testing. The key is to select a piezoelectric material that is not very sensitive to
temperature changes over the operating temperatures of interest. Alternatively, temperature compensation or other calibration schemes can be adopted.

Generally speaking, dielectric constants, piezoelectric constants, and coupling factors of the harder piezoelectric materials are more stable with respect to temperature than softer materials (www.alphapiezo.com). However, properties of softer materials generally exhibit a linear relationship to temperature over a broad temperature range and hence a more easily “calibratable.” Therefore, depending on the application of interest, it is possible to minimize or compensate for thermally induced variations in piezoelectric properties.

Figure 5 through Figure 7 present examples of how the electromechanical planar coupling coefficient, $k_p$, stress coefficient, $g_{31}$, and strain coefficient, $d_{31}$, vary with temperature for three piezoelectric materials (Morgan Electroceramics TP-226 n.d.).

Another important thermal property is the linear coefficient of thermal expansion (CTE). The CTE of PZT-4 and PZT-5A is extremely anisotropic on first heating particularly above 50°C (122°F) (Morgan Electroceramics TP-226 n.d.). On subsequent heatings, the CTE is more or less stable for both materials up to about 100°C (212°F). The CTE of a PZT-5A ceramic in the direction perpendicular to the poling axis is roughly 4 mm/mm/°C (2.2 in/in/°F) which is approximately 4.5 times lower than that of stainless steel. This dissimilarity is relevant when using duomorph benders with a metal shim operated to harvest the converse effect.

### 2.3.3 Relations of Piezoelectricity

The basic constitutive equations for the linear theory of piezoelectricity given by Jaffe and Berlincourt (1965) are:

$$ D = \varepsilon^s E + e \varepsilon, $$

$$ \sigma = -e^s E + c^E \varepsilon $$

Eq. 2
Figure 5. Sample plot of variation of $g_{31}$ as a function of temperature (redrawn from Morgan Electroceramics TP-226 n.d.).

Figure 6. Sample plot of variation of $d_{31}$ as a function of temperature (redrawn from Morgan Electroceramics TP-226 n.d.).
Figure 7. Sample plot of variation of $k_p$ as a function of temperature (redrawn from Morgan Electroceramics TP-226 n.d.).

where,

\[ D = \text{Electric displacement, Coulomb (C)/m}^2 \]

\[ \varepsilon = \text{Permittivity, Farad (F)/m} - \text{usually expressed as dielectric constants K} \]

\[ = \varepsilon / \varepsilon_0; \text{where, } \varepsilon_0 \text{ is the permittivity of free space} = 8.85 \times 10^{-12} \text{ F/m}. \]

\[ E = \text{Electric field strength, Volt (V)/m} \]

\[ e = \text{Piezoelectric stress constant, C/m}^2 \text{ or N/Vm} \]

\[ \varepsilon = \text{Mechanical strain, m/m} \]

\[ \sigma = \text{Mechanical stress, N/m}^2 \]

\[ c = \text{Elastic stiffness, N/m}^2 \]

In addition, the superscripts S and E in equation 2 describe the following electrical or mechanical boundary conditions:

\[ S = \text{constant strain (mechanically clamped)} \]

\[ E = \text{constant field (short circuit)} \]
The piezoelectric constitutive equations can also be expressed in matrix notation as (after Barnett et al. 2001):

\[
\mathbf{\sigma}_{6 \times 1} = [c]_{6 \times 6} \mathbf{\varepsilon}_{6 \times 1} - [e]_{6 \times 3}^{T} \mathbf{E}_{3 \times 1} \quad \text{Eq. 3a}
\]
\[
\mathbf{D}_{3 \times 1} = [\varepsilon]_{3 \times 3} \mathbf{E}_{3 \times 1} + [e]_{3 \times 6} \mathbf{\varepsilon}_{6 \times 1} \quad \text{Eq. 3b}
\]

The notation shown in equations 3a and 3b is called the stress-charge form; taken after the independent variables in the equation. Alternate ways of defining the basic piezoelectric constitutive equation also exist including strain-charge, stress-voltage, and strain-voltage forms (Jaffe and Berlincourt 1965, efunda.com n.d.).

It is obvious from equation 3 that in order to completely define the behavior of a piezoelectric material, 9 dielectric constants (or permittivities), 18 piezoelectric stress (or strain) constants, 36 elastic stiffness (or compliance) constants are needed as a minimum notwithstanding more general dielectric, piezoelectric, and elastic behavior. Fortunately, the materials of interest in this study have high symmetry which greatly simplifies the materials characterization.

2.4 The Duomorph -- Operating Principle and Applications

A piezoelectric element can be given a preferential mode of operation, i.e., elongation, flexure, or shear depending upon the applied electrical field/charge or mechanical strain/stress, the orientation of the polarization axes, stacking of the individual piezoelectric layers, etc. Of particular relevance to this research are flexurally responsive piezoelectric elements. There are several piezoelectric elements that qualify as flexure mode transducers or gages including unimorphs, duomorphs, multimorphs and other multi-electroded, single-poled, specially treated single-plate elements. However, historically the most popular element has been the duomorph, which, is a layered assembly of a metallic shim placed between two piezoelectric sheets. The overall thickness of the gage is in the order of half a millimeter. The different layers in the duomorph are held together by a fine layer of a special bonding agent.
The exposed surfaces of the piezoceramic layers are coated finely with electrodes (silver, nickel, etc.) to enable electrical connections. Thin electrical leads are soldered to the surface of these electroded faces to facilitate electrical excitation or measurement. The piezoelectric sheets are thickness poled and are arranged either in series (i.e., both poling axes point in the opposite directions) or parallel (i.e., both poling axes point in the same direction) about the neutral axis of the duomorph assembly. The choice between series and parallel type will depend on many individual factors which will be discussed in detail in the next chapter.

Figure 8 (a) and (b) present plan and section sketches of the duomorph gage. The particular shape preferred for this research is the circular disc shaped bending element similar to those used in microphones, headphones, alarms, etc. The reason for this choice is tied to historical roots surrounding the use of the duomorph for material characterization. This is related to the fact that, a circular disc shaped bending element has a relatively well-known analytical solution in the mechanical domain.

![Figure 8. The duomorph/DART gage.](attachment:image.png)
2.4.1 Operating Principle of the Duomorph

The piezoceramic layers function as electromechanical transducers capable of producing an electrical voltage when a mechanical deformation is applied to them and vice versa. When a voltage is applied to a PZT crystal it deforms, i.e., expands or contracts. In an electrically asymmetric duomorph gage (such as the one shown in Figure 8), the poling axes of the two piezoceramic layers are oriented such that, when a voltage is applied across their electroded faces, one of the layers expands while the other contracts. In such “parallel type” duomorphs the electroded piezoelectric faces are driven simultaneously with a voltage of like polarity with respect to an electrical “ground” contact established with the metal vane. This produces a bending action as indicated in the section view of the gage shown in Figure 9. It is clear from the figure that the maximum bending strain occurs at the center of the gage. Therefore, this is an ideal location for strain gaging – a preferred technique for gage response measurement in this research which is preferred over direct measurement of the piezoelectric electrical response.

![Figure 9. The duomorph in operation.](image)

The magnitude of the bending strain at the gage center is directly proportional to the driving voltage. In fact, it has been observed in the laboratory that the amount of bending is increases linearly with the applied voltage. While higher driving voltages are required to obtain cleaner signals (lower signal-to-noise ratio) particularly when the gage is embedded in a viscoelastic medium (e.g., asphalt), care must be taken to ensure that the driving voltage does not cross the depolarization limit of the duomorph. If this happens, the duomorph will lose its piezoelectric properties and will behave like an ordinary ceramic.
If the applied voltage signal is sinusoidal, the sensor vibrates sinusoidally at the same frequency as that of the input signal. When the duomorph gage is operated in air, the strain signal should exactly follow the trace of the driving voltage, i.e., the time lag or “signal shift” is zero. This provides a calibration point for analysis when the gage is embedded in asphalt. However, when the gage is embedded in a viscoelastic medium and vibrated, two significant changes occur to the signal. First, there will be a time lag induced in the response of the gage with respect to the applied driving voltage signal. Second, the peak strain will be reduced due to the confining effect of the stiffness of the surrounding medium. The signal shift along with the ratio of peak duomorph gage strains in air and in the medium, provides a means to compute the properties of interest of the surrounding medium. For the case of asphalt materials the properties of interest are the $G^*$ and $\delta$ of the viscoelastic medium.

Figure 10 presents a schematic of the duomorph operation, illustrating experimental determination of the signal shift. It is important to note here that the shift in the bending strain response is not the same as the phase angle, $\delta$, of the asphalt binder. In fact, phase angle is just one of the parameters on which the signal shift is dependent upon. Other factors that influence this parameter include the stiffness of the surrounding medium and the geometric and material properties of the duomorph itself.

![Figure 10. Schematic of duomorph operation illustrating gage strain and signal shift determination.](image-url)
2.4.2 Past Material Characterization Applications of Duomorph

2.4.2.1 Long-Term Surveillance of Solid Rocket Propellant Integrity

In the 1970s the Air Force Rocket Propulsion Laboratory (AFRPL) established a program to obtain unobtrusive yet “meaningful” surveillance of solid rocket propellant grain in ballistic and tactical missiles. As part of this program, Briar and Bills (1972) and Briar et al. (1976) investigated the use of the duomorph as a permanently embedded sensor for long-term surveillance of the structural integrity of solid rocket propellant—which was later on proposed as a means to characterize viscoelastic materials. This pioneering study was the main source of inspiration and engineering basis for this dissertation.

The justification for this program was based in the following factors (1) conventional testing of solid rocket propellant fuel involved testing unrepresentative samples of materials and single-point material characterization, (2) the effect of aging on physical and ballistic properties needed to be tested in a continuous monitoring environment to assess the “worthiness” of weapon systems in real time; single point determinations done by conventional tests were deemed meaningless, (3) the accelerated aging techniques prevalent at the time to age propellant materials misrepresented the natural aging process, and (4) dynamic testing needed to be performed in order to capture the frequency range of greatest interest in the relaxation spectrum of the propellant.

As part of the AFRPL program, Briar and Bills (1972) developed a telemetry package—with the duomorph as its central component propellant property determination—to follow the loads, deformations, and grain material properties as the motor is stored, transported, handled, and eventually fired. In fact, the term “duomorph” was coined during this study. Before settling on the duomorph for sensing propellant properties and their changes with aging, Briar and Bills (1972) investigated other piezoelectric gages including piezoelectric stacks and unimorphs. Apart from the development of the duomorph, Briar and Bills (1972) also focused on the development of wireless techniques to remotely access the duomorph sensor embedded into the propellant grain for actuation and sensing purposes. The research of Briar and Bills (1972) and Briar et al. (1976) was undertaken in two phases. Phase I focused on proof of concept, shakedown testing, telemetry package development, and
rudimentary analytical modeling. Phase II refined the duomorph sensor and sensor electronics and developed a final prototype and the associated analytical modeling tool for data reduction to estimate propellant properties.

2.4.2.2 Phase I – Feasibility Test
In Phase I, several prototype duomorph sensors were developed and tested to determine their operating characteristics in air and in the propellant held at various temperatures. The duomorph sensors used were made up two 0.009-in (0.23 mm) thick piezoceramic disks of the PZT-4 type concentrically mounted on either side of a 0.008-in (0.20 mm) thick stainless steel disk. The diameter of the stainless steel disk was 1.35-in (34.29 mm), whereas, the PZT disks were 1-in (25.4 mm) in the final duomorph that evolved out of Phase I. Brass disks were used initially but were later rejected due to undesirable chemical reactions (oxidation) of this material with the surrounding propellant medium. One of the PZT disks was used as a driver and the other as the sensor of the resultant electrical response.

The feasibility of using the duomorph to characterize propellant grain was established through simple response testing involving a creep and stress relaxation tests. The duomorph performed according to theory for this type of testing. Dynamic testing with an external alternating current (AC) field was performed to investigate the ability of the sensor to characterize the material at the frequency ranges of interest. The testing showed that the duomorph was sensitive to changes in the viscoelastic properties and masses in the surrounding medium. However, some analytical issues pertaining to data reduction for dynamic testing precluded any final conclusions to be made regarding the accuracy of the material characterization abilities of this device vis-à-vis other conventional devices.

2.4.2.3 Phase II – Advanced Analytical Modeling
In the second phase of the research program, Briar et al. (1976) further refined and developed the duomorph sensor design. They formulated better numerical formulations to analyze gage behavior in air and in the continuum and compared duomorph derived material properties to properties of the propellant grains tested by other means. Finally, they refined the telemetry systems for remotely determining in situ properties of the solid rocket propellant.
Four duomorph models illustrated in Figure 11 were developed in this work. It included the original duomorph (Model A) developed in Phase I, a symmetrically driven duomorph (Model B) with strain gages which is a variant of Model A, an asymmetric duomorph with strain gages (Model C), and an asymmetrically driven duomorph with guarded PZT sensing (Model D). The development of these gages paralleled the researchers’ understanding of the devices and their manner of operation. After carefully, reviewing the needs of their research, Briar et al. concluded that although Model B would be ideal for laboratory testing and for monitoring aging changes in propellant, Model D was specifically suited for their purpose due to its lower power requirements and higher frequency range.

Figure 11. Evolution of the duomorph designs (Briar et al., 1976).

Briar et al. (1976) developed theoretical relations to predict gage response when it is embedded completely within a viscoelastic medium as well as when it is applied as a surface gage. The initial theoretical development was for the Model B type gage which was eventually extended to be applicable to the Model D gage which was their gage of choice. Using this analytical tool as a basis, Briar et al. (1976) developed a procedure to “backcalculate” or estimate the properties of the viscoelastic medium—complex modulus $E^*$.
and δ—knowing gage responses under an applied electrical excitation. This mathematical procedure involved consideration of the duomorph gage as a thin plate structure and the propellant as a linear viscoelastic medium infinite in extent. The entire procedure was implemented using a normographical approach primarily developed for the Model D duomorph.

The data reduction process was validated using limited testing of rubber, soft clay, solid propellants, and asphalt materials. For these materials, known complex moduli determined from other standard tests were compared to those backcalculated from the duomorph testing. Based on this comparison it was concluded that, although the data were limited, the duomorph had the potential for producing propellant moduli to a reasonable degree of accuracy and to any arbitrary degree provided development cost was not a factor.

Several similarities exist between the research conducted by Briar and Bills (1972) and Briar et al. (1976) and the research documented herein. These are:

- Briar and Bills (1972) and Briar et al. (1976) studied the application of the duomorph for characterization of viscoelastic materials much like the subject research.
- There is a significant overlap in the materials properties of interest between the two studies.
- Similarities exist between the test setup and ranges of test temperatures, excitation and sensing characteristics, and test frequencies.

This pioneering study therefore not only provided the basis for the exploring the possibility of using the duomorph for asphalt testing but also provided the technical basis from where the technology could be redeveloped and adapted.

2.4.2.4 Asphalt Concrete Characterization

Encouraged by this research, Boggess and Noel (1980) extended the concept to in situ estimation of the dynamic stiffness of hot-mix asphalt layer in flexible pavements. In this
study, Boggess and Noel (1980) conceived the duomorph as an expedient technique to estimate the dynamic stiffness of the asphalt layer to facilitate a more accurate numerical deduction of layer moduli based on deflections obtained from truck-mounted pavement loading devices. The alternative to determine dynamic stiffness at that point in time was to use more elaborate laboratory testing schemes which were time consuming and expensive.

Boggess and Noel (1980) used the duomorph as a surface gage, i.e., the gage was placed on top of the pavement and held in place using a slight pressure. For the duomorph to function in this mode, the pavement surface has to be smooth to ensure even contact and the duomorph has to be held down firmly using some amount of external pressure to ensure good contact. To satisfy these conditions, the pavement surface was ground using a hand-held grinding device just prior to testing and the gage was held down using a silicone rubber block with a low modulus (~300 psi or 2 MPa) with a superimposed pressure applied to it using a force plate. A low modulus silicone block was used to transmit the pressure from the force plate since it does not increase the stiffness of the duomorph gage assembly.

The duomorph used was similar to Model B shown in Figure 11 complete with asymmetrically poled piezoceramic layers (see Figure 8), a central metal shim made of brass, and strain gages. The other interesting features of the gage design and operating features are as follows:

- The two outer electroded faces of the duomorph were shorted and driven with respect to the electrical ground established by accessing the metal disk. Shorting the electroded faces and driving them using the same AC voltage signal (from the same source and with like magnitude and polarity) eliminates the possibility of capacitatively coupling the drive signal into the measured strain response.
- A drive voltage of ±250 V was deemed necessary to create measurable motion in the flexible pavement system. Two Kepco power supplies were used to meet the high voltage and high power (approx. ~300 ma at 1000 Hz) requirements.
- An AC drive signal was used and the operating frequencies ranged from 0.1 to 100 Hz.
• Strain gages were used to measure the alternating flexural strains. To further eliminate the capacitative coupling of the drive signal with the measured response, AC excitation was supplied to the strain gage bridge.
• An amplifier with a band pass of 2500 Hz and capable of resolving strains of less than 1.5 microstrains was used to amplify the measured strains.

The strain data collected from the duomorph in air (unconstrained) and when was resting against the pavement at a given frequency were used to estimate the viscoelastic properties of the asphalt layer (primarily the dynamic modulus) using the methodology derived by Briar et al. (1976) for structurally symmetric (Model B) gages. Based on limited comparisons with laboratory measurements of dynamic moduli performed at 2 Hz from core samples collected on two Texas routes (US 83 and Texas 493), it was concluded that the duomorph is a viable tool for modulus estimation. Moduli from the duomorph were estimated at a number of frequencies ranging from 0.1 to 100 Hz.

2.4.2.5 Marine Sediment Characterization
In the mid-1990s, Lavoie, et al. (1996), under funding from the Naval Research Laboratory, further extended the original duomorph concept and applied it to the testing of marine sediments. Their application termed DIAS – the Duomorph In Situ Acquisition System – was used to estimate the shear modulus properties of the sediment. Accurate measurements of sediment elastic moduli are required for better prediction of acoustic scattering and propagation and for many engineering applications (Lavoie, et al., 1996). Traditionally, sediment geoacoustic properties are measured using in situ pulse techniques which require multiple probes and very accurate knowledge of probe placement, difficult to achieve in the marine environment. An alternate way to measure the properties of the sediment is to sample and analyze them in the laboratory which requires significant disturbance of the sample and potential changes to the properties of the sediment. The duomorph therefore offers a particularly attractive alternative to estimate the elastic moduli of marine sediments because it is an in situ test.
The DIAS comprised of duomorphs built with varying thicknesses (0.008-in, 0.005-in, and 0.0003-in) of stainless steel plates in order to determine the best configuration for the sediment being analyzed. The piezoceramic material used was a G-1278 type (similar to PZT-5H), fired silver, with a thickness of 0.011-in and a diameter of 1-in. Each piezoceramic layer was strain gaged in a manner similar to the Model B gage shown in Figure 11 with their polarization axes arranged asymmetrically about the neutral axis (see Figure 8). The entire duomorph sandwich was potted into a circular, stainless steel probe blade using a low derometer, multi-purpose elastomer. The blade was required to provide protection for the delicate ceramic sandwich during probe insertion. The blade was attached to a pressurized chamber via a hollow shaft which houses the system electronics for gage actuation and data acquisition purposes.

A sinusoidal signal with 40 volt peak-to-peak signal at 250 Hz frequency was employed as a forcing function. The electroded faces of the gage were shorted and driven simultaneously with respect to an electrical ground established by accessing the metal shim. The metal shim was accessed by first creating a tab-like projection around the periphery of the gage and then filing off the peizoceramic layer from it until the metal is exposed. A lead wire is then soldered on to this tab which is then connected to the ground terminal of the power supply. It was realized during the testing process that, to obtain valid results, the probe needed to remain in place until the pore pressure in the sediment being measured has equilibrated – estimated by monitoring the amplitude of the DIAS signal measured for stability.

The data reduction techniques employed by Lavoie et al. (1996) were based on those derived by Briar et al. (1976). However, Grosz, a member of the research team, automated the nomographical data reduction procedure through the use of a copyrighted computer program. This program makes the data reduction process relatively easy.

Limited testing of marine sediments conducted at Eckenforde Bay suggested that the DIAS produced results that were consistent and reliable. The prototype system was deemed viable for further development.
2.4.3 Refinements Needed for Asphalt Binder Testing

A close review of the past studies indicates that the duomorph has the potential to function as a supplemental test device to a variety of testing situations and test equipment. Inasmuch as past studies have showcased the application of the duomorph technology to determine properties of viscoelastic materials quickly and reliably, a few issues exist that necessitate further redevelopment before its adoption for asphalt binder testing. Some of these are listed below:

- It is nearly three decades since the duomorph was first conceived for the characterization of viscoelastic materials. Several technological advancements in piezoelectric materials, instrumentation, signal conditioning, numerical modeling, etc., have taken place since then and need to be considered to upgrade the state-of-the-art in applying the duomorph for materials testing.

- Further, much of the previous work was concerned with the estimation of stiffness of the medium being evaluated (i.e., some measure of complex modulus). Although, the estimation of phase angle is coincidental to the estimation of the complex modulus of a given medium, not much attention was paid to the assessing the feasibility of the duomorph to accurately estimate the phase angle term. For asphalt binder testing, particularly during specification compliance testing, both terms are important and the data reduction process needs to be able to accurately resolve both these terms. Optimizing theoretical procedures to yield satisfactory results for multiple parameters is obviously more challenging than considering a single parameter.

- Briar et al. (1976) concluded that fuel-rich layers, similar to soft asphalts would be hard to evaluate using a duomorph. Boggess and Noel (1980) note that the sensitivity of the gage is a function of the stiffness of the medium being tested and as a consequence different gages may be needed for different consistencies of the medium under evaluation. Both these contentions need further verification to study the applicability of the duomorph for asphalt binder testing.
These and other concerns, e.g., applicability and accuracy of past analytical representation of the duomorph gage behavior and the gage-continuum interaction, warranted the redevelopment effort undertaken in this dissertation.
CHAPTER 3. DEVELOPMENT OF THE DART

The two main tasks in the development of the DART system are (a) the design of optimally sized DART gages, and (b) the design of suitable electronic sub-system capable of driving the gage and obtaining data from it. This chapter details the evolution of the DART system including a description of the DART gages considered suitable for asphalt binder testing, the electronic sub-system, and signal excitation and data logging software. Also contained in this chapter is a description of the shakedown tests conducted to evaluate the viability of the DART to perform asphalt binder testing. Finally, results of repeatability and reproducibility and the potential accuracy of the DART are also discussed.

3.1 DART Gage Design

As explained in Chapter 2, the DART gage comprises of the two concentrically placed piezoceramic sheets with or without a metal shim in between. Even with this simple structural arrangement, several gage parameters can be altered to realize an array of combinations with differing performance characteristics.

In this study, several of the parameters were varied and laboratory experiments conducted to study the mechanical behavior of the gage in air (unconstrained) and when embedded in asphalt (constrained). A study of the unconstrained gage response was necessary to establish a calibration reference to which the constrained gage responses could be compared with. A study of the constrained gage response was necessary to establish ranges of asphalt viscoelastic properties over which the DART would be useful. The following basic questions were attempted to be answered in the constrained gage response study:

- Over what ranges of asphalt binder stiffness is the DART effective and what are the desired dimensions and other pertinent specifications to which the gage should be manufactured?
• Is there a relationship between the DART’s physical dimensions, material properties, and operating characteristics and the properties of the asphalt binder in which it is operating?
• What is the optimal asphalt binder specimen dimensions required for testing?
• What operating/testing parameters of the DART need to be optimized to ensure that the asphalt binders being tested are always within the linear viscoelastic regime as required by AASHTO R 29 “Grading and Verifying the Performance Grade of the Asphalt Binder” and AASHTO T 315 “Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer”?
• Is the response of the DART gage a function of the drive frequency and ambient temperature? If so, how can they be accounted for in routine testing?

Some of the parameters available to optimize the gage design include:

• Shape of the gage – circular, rectangular, square, etc.
• Piezoelectric material – ceramics (e.g., PZT-4, PZT-5A, PZT-5H, etc.), plastics, etc.
• Type of center shim or vane – no shim, stainless steel, brass, etc.
• Dimensions of the gage (diameter, thickness of the individual layers of the sandwich assembly).
• Arrangement of the thickness polarization axis of the piezoelectric material about neutral axis – symmetric or series-poled (i.e., both poling axes point in opposite directions) or asymmetric or parallel-poled (i.e., both poling axes point in the same direction).

In addition, the following non-gage related parameters can also be varied to study their impact:
- Size of the asphalt specimen to be utilized for testing.
- Gage actuation – both disks are driven simultaneously with respect to a fixed ground reference (usually the metallic shim) or one disk is driven while the other is grounded.
- Strain or deflection sensing method adopted – use of strain gages when both sides of the piezoelectric disk are driven (i.e., used as actuators) or using the piezoelectric disk as both an actuator and a sensor (in this case, only one side of the disk is driven and other side is passive).

3.1.1 Early Decisions Regarding Gage Design

Although generally speaking, all the aforementioned gage geometry, materials, actuation and deflection sensing variables were possible to be investigated, after a preliminary review of practical aspects of constructing the devices and obtaining meaningful information from them as well as the lessons learned from past work with the duomorph described in Chapter 2, it was determined that some of the factors had to be constrained. One of the early decisions made in the gage design parameter selection process was to adopt only circular gages. This was done to maintain continuity with past research (all previous studies used circular gages). Also, the analytical schemes developed from past studies to reduce the gage outputs for material characterization purposes were based on circular gages.

Another decision was to use strain gages to measure bending strains induced by the application of electrical charge to the outer faces of the gages rather than using the piezoceramic as both an actuator and a sensor. This was done to reduce the effects of signal “drifts” due to variations in testing temperature or due to static preload when the gage is embedded in asphalt at lower temperatures. Also, creating electrical sense spots to measure piezoelectric output voltages requires special manufacturing specifications which increase costs. Furthermore, strain gages, besides being cost-effective, are easy to install and simpler to calibrate at different testing conditions. For the most part, bonded resistance foil strain gages were used; however, bonded semiconductor strain gages were experimented with
briefly but unsuccessfully (primarily owing to the specialized nature of installation of these gages and cost).

Finally, PZT-5A material was selected for use in this research due to its superior performance in terms of resistivity at elevated temperatures and higher time stability when compared to PZT-5H material. The latter material has higher electromechanical coupling coefficients and dielectric constants – key properties determining the effectiveness of the DART over the stiffness range of interest in asphalt binder testing (see Table 2). However, the time and temperature stability of PZT-5A were deemed to be more important for this research because the asphalt temperatures that the DART gage will experience during embedment and disembedment from the asphalt medium are expected to span the regions where the piezoelectric properties of the PZT-5H material exhibits pronounced nonlinear behavior. With the exception of PZT-5H material, the PZT-5A material has a higher sensitivity compared to many other piezoelectric materials.

<table>
<thead>
<tr>
<th></th>
<th>PZT-5A</th>
<th>PZT-5H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative dielectric constant at 1 KHz ((K_{33}^T) - 3 is thickness direction of the DART gage), free ((\varepsilon_{T}/\varepsilon_{o}))</td>
<td>1800</td>
<td>3800</td>
</tr>
<tr>
<td>Electromechanical coupling factor, (k_{31})</td>
<td>0.35</td>
<td>0.44</td>
</tr>
<tr>
<td>Piezoelectric constant (d), strain/field at constant stress or charge short circuit charge density/stress at constant electric field, meters/volt.</td>
<td>(-190\times10^{-12})</td>
<td>(-320\times10^{-12})</td>
</tr>
<tr>
<td>Curie point</td>
<td>365°C (690°F)</td>
<td>193°C (380°F)</td>
</tr>
</tbody>
</table>

Note: The subscripts in the table reference a Cartesian coordinate system with the 1 and 2 directions denoting the in-plane axes of the DART gage and the 3 direction denoting axis perpendicular to the plane of the gage (i.e., thickness direction).

With the exception of the aforementioned decisions, all other parameters of the gage design were experimented with in this study to determine the most optimal DART system design.
3.1.2 *Gage Parameters used in Evaluation*

The final experimental matrix to evaluate the ability of the DART gage to determine asphalt properties evolved as testing progressed and results were analyzed. At each step adjustments were made to the geometry, materials, thicknesses, and actuation methods to determine the most reliable and rugged device for testing. The process led to the consideration of the various gage parameters at the following factor levels:

- PZT layer thickness – 1 level.
- Type of backing materials – 3 levels (steel, brass, and no shim).
- Thickness of backing material – 2 levels (0.004, 0.005 and 0.008-in).
- Thickness of PZT material – 2 levels (0.005 and 0.0075-in).
- Gage diameter – 4 levels (0.5 in, 0.75 in, 1 in, and 2 in).
- Poling axis orientation of PZT layers with respect to neutral axis – 2 levels (symmetric or series poled and asymmetric or parallel poled). The term symmetric implies that the poling axes of the PZT layers in the gage point in opposite directions about the neutral axis, i.e., they point away from each other or toward each other. Asymmetric gages are those where the poling axes of the PZT layers point in the same direction. Figure 12 presents symmetric and asymmetric gages.

![Diagram](image)

(a) Electrically symmetric or series type gage  
(b) Electrically asymmetric or parallel type gage

Figure 12. Illustration of symmetric and asymmetric duomorphs.

Table 3 presents a list of the various DART gages considered in this study along with key parametric values. Also noted in the table are the flexural rigidities of a given gage, D. This parameter is computed using equation 4 (Briar and Bills 1972) and is based on the assumption that the gage assembly is a perfectly bonded linear elastic system characterized using a single Poisson’s ratio (a reasonable approximation considering the quality of bond of
the commercial product chosen for this work and the closeness of the Poisson’s ratios of steel and the PZT-5A material). This term quantifies the flexural stiffness of the gage and is very important in establishing the asphalt binder stiffness regimes over which each gage is expected to yield satisfactory performance. The initial premise based on the work of Grosz et al. (Grosz, Griffin, & Wei, 2000) being that higher the gage stiffness, the more applicable it is to testing stiffer asphalts, and vice versa.

Table 3. Dimensions and flexural rigidities of the DART gages assembled.

<table>
<thead>
<tr>
<th>DART Gage Description</th>
<th>Disk Thickness, mils</th>
<th>Diameter, in</th>
<th>Flexural Rigidity, D lbf-in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Poling Axis Orientation</td>
<td>PZT</td>
<td>Center Shim</td>
</tr>
<tr>
<td>DART # 1A</td>
<td>Symmetric</td>
<td>7.5</td>
<td>8 (Steel)</td>
</tr>
<tr>
<td>DART # 1B</td>
<td>Symmetric</td>
<td>0.75</td>
<td>10.04</td>
</tr>
<tr>
<td>DART # 1C</td>
<td>Symmetric</td>
<td>0.5</td>
<td>10.04</td>
</tr>
<tr>
<td>DART # 2A</td>
<td>Symmetric</td>
<td>7.5</td>
<td>5 (Steel)</td>
</tr>
<tr>
<td>DART # 2B</td>
<td>Symmetric</td>
<td>0.75</td>
<td>6.89</td>
</tr>
<tr>
<td>DART # 2C</td>
<td>Symmetric</td>
<td>0.5</td>
<td>6.89</td>
</tr>
<tr>
<td>DART # 3A</td>
<td>Symmetric</td>
<td>7.5</td>
<td>4 (Steel)</td>
</tr>
<tr>
<td>DART # 3B</td>
<td>Symmetric</td>
<td>1.0</td>
<td>6.03</td>
</tr>
<tr>
<td>DART # 3C</td>
<td>Symmetric</td>
<td>0.75</td>
<td>6.03</td>
</tr>
<tr>
<td>DART # 4A</td>
<td>Asymmetric(^2)</td>
<td>7.5</td>
<td>4 (Steel)</td>
</tr>
<tr>
<td>DART # 4B</td>
<td>Asymmetric(^2)</td>
<td>0.75</td>
<td>6.03</td>
</tr>
<tr>
<td>DART # 5A</td>
<td>Symmetric</td>
<td>7.5</td>
<td>–(^1)</td>
</tr>
<tr>
<td>DART # 6A</td>
<td>Symmetric</td>
<td>7.5</td>
<td>5 (Steel)</td>
</tr>
<tr>
<td>ADART # 1</td>
<td>Asymmetric(^3)</td>
<td>7.5</td>
<td>5 (Steel)</td>
</tr>
<tr>
<td>ADART # 1B</td>
<td>Asymmetric(^3)</td>
<td>7.5</td>
<td>5 (Steel)</td>
</tr>
<tr>
<td>ADART # 1C</td>
<td>Asymmetric(^3)</td>
<td>7.5</td>
<td>5 (Steel)</td>
</tr>
<tr>
<td>ADART # B2</td>
<td>Asymmetric(^3)</td>
<td>5.0</td>
<td>5 (Brass)</td>
</tr>
</tbody>
</table>

1 mil = 0.0254mm; 1 in = 25.4 mm; 1 lbf-in = 0.11 kN-mm.
1 No metal shim was used in this gage.
2 These disks were originally symmetrically poled as procured from the manufacturer; their poling was reversed by applying a high DC voltage in the laboratory.
3 These disks were procured as asymmetrically poled from the manufacturer.

\[
D = \frac{E_z h^3}{12(1-\nu^2)} \left[ 1 + \left( \frac{E_m}{E_z} - 1 \right) \left( \frac{h_m}{h} \right)^3 \right] \quad \text{Eq. (4)}
\]

where,

\(D\) = gage flexural rigidity
\(E_z\) = modulus of the PZT disk
\(E_m\) = modulus of the metal disk
\begin{align*}
  h_m &= \text{thickness of metal disk} \\
  h &= \text{overall thickness of the DART gage}
\end{align*}

As mentioned earlier, the continual evaluation of the effectiveness of the DART gage to determine the required asphalt binder properties in the laboratory drove the construction of various gage types. This evaluation progressed in two phases. Phase I involved configuring rudimentary gages (Briar & Bills 1972, Briar et al. 1976, Lavoie, Griffin, & Grosz, 1994) with varying dimensions and performing proof-of-concept testing (i.e., testing done to verify the concept that the gage response is sensitive to asphalt materials) and shakedown testing (i.e., testing done to finalize test configurations and settings). In Phase I, gage diameters were varied at four levels—0.5-in, 0.75-in, 1 in, and 2-in. The thickness of piezoelectric layer had to be held constant at 0.0075 in because this was the only thickness that could be economically procured from the piezoceramic material supplier. Further, only stainless steel based metallic backing material was used in this phase of the study and its thickness was varied at two levels—0.005 and 0.008 in. Thus, the overall gage thickness was either 0.020 in or 0.023 in. DART # 1A through DART # 3C in Table 3 were developed under Phase I. Note all these gages were symmetric or series poled.

It was empirically observed in Phase I study that a more sensitive gage (i.e., one which would produce more deformation per volt) would be required at the elevated testing temperatures when the gage is embedded in asphalt. For this reason, in Phase II, more slender DART gages made with thinner backing material made out of brass were investigated alongside the stainless shim-based gages. The objective behind introducing a thinner shim made with a lower modulus metal was to increase the gage sensitivity by decreasing the lower overall flexural rigidity of the gage. In addition, a shimless gage (i.e., a gage with no metallic shim in the center) was also investigated. Gages DART # 4A through ADART #B2 in Table 3 were developed under Phase II. Note that several of these gages were asymmetric or parallel poled.
3.2 DART Gage Preparation

3.2.1 Manufacturing the Circular Gages

PZT-5A piezoceramic material bearing the trade name, PSI-5A-S2, from Piezo Systems, Inc., Cambridge, MA were used in this research. The material is procured as rectangular sheets which are manufactured in terms of types of layers, thicknesses of layers, layer arrangement, poling orientations of the piezoelectric sheets, etc., per specifications. The sheets are nickel electroded on either side. Circular disks of specific dimensions were cut from these rectangular sheets. The following steps were followed in preparing the circular DART gages:

1. With a non-lead based marker, the area to be cut from the rectangular sheets was marked.
   a. For Phase II DART gages, a small triangular tab, which was needed to access the center shim to enable simultaneously driving the asymmetric gages, was also marked.
2. Using a small, hand held cutting tool comprising of solid carbide blades mounted on a rotating shaft, the rectangular ceramic sheets were cut to the desired dimensions ensuring that smooth edges with minimal chipping of the piezoceramic sheets resulted.
3. The DART gage obtained from the cutting process in Step 2 was brushed along its circumference with a rotating soft brush to ensure any loose ceramic and metal particles are removed. The final product acceptance was based on a subjective evaluation of the quality of the cuts made, the smoothness of the edges, and the extent to which the gage surface is impacted by the cutting operation. In all, this was deemed adequate for a laboratory prototype.

Figure 13 illustrates how the rectangular sheets are marked to accommodate the circular dimension of the gage and tab connection for a 1-inch gage.
3.2.2 Poling Orientation of the Gages

- All the PZT layers used in the DART gages mentioned in Table 3 were thickness poled (i.e., poling axis is parallel to the thickness direction). However, as noted, Phase I gages were arranged for series operation (symmetric orientation of the poling axes with reference to the neutral axis of the gage). This meant that only one face of the gage could be driven with an AC signal while the other was grounded. In this arrangement, an access to the center shim for grounding purposes was therefore optional; in fact, none of the Phase I gages had the metal tab indicated in Figure 13. In Phase II testing, bulk material configured for parallel or asymmetric operation were procured and circular discs were cut from such material. However, as noted in Table 3, some of the earlier version asymmetric gages (DART #4A and #4B) were manufactured from symmetrically poled raw piezoelectric sheets procured from the manufacturer. The poling orientations were reversed in the laboratory to make them asymmetric gages. The following steps were followed in the laboratory to accomplish this:
Exposed a small area of the metallic center shim of the DART gage bulk sheets by carefully filing off the PZT layers as was suggested by Lavoie et al. (1996).

Soldered one lead to the exposed part of the center shim and 2 leads to the outer faces of the gage bulk sheets (i.e., electroded portions of the piezoceramic sheets) via insulated solder material.

Shorted leads from the center shim and the PZT layer that is not being repoled (to electrically protect the latter) and connected them to the positive terminal of a DC source. Connect the lead wire from the PZT layer that is being repoled to the negative terminal of the DC source. Note, this arrangement will work if the poling axes point away from the neutral axis of the DART bulk material as shown in Figure 12(a). However, if the poling axes point toward the neutral axis, the connections to the DC source will need to be reversed.

Slowly and carefully increased the applied electric field in a manner that changes the from 0 to 350 V in approximately 60 seconds taking care not to exceed 400 V at any time to avoid excessive current build-up and arcing. At this point the disk is repoled and the poling axis is reversed.

Turned down the applied electric field slowly and disconnected the DC source.

This entire operation was performed under expert supervision and with proper safety gear to avoid untoward accidents. To further enhance safety, a 100 kilo-ohm resistor was connected in series with the bender element to limit current supply. According to manufacturer reports, a piezoceramic bender element repoled in this way performs to 85 to 90 percent levels when compared to manufacturer produced material.

A total of seventeen different DART gage prototypes were manufactured and tested in the laboratory under Phases I and II. In some instances multiple gages with similar configurations were developed to evaluate repeatability of the process.
3.2.3 Strain Gages and Electrical Leads

The type of strain gages, leads, bonding agents used and the methods employed in attaching strain gages to the DART gages were modified throughout the research in search of the optimal configuration to provide consistency and improve the durability of the DART. These parameters were finalized in Phase II. Strain gages from Micro Measurements, Inc., of the type EA-06-125AC-350 with a gage length of 0.122 in were adopted. These gages come with pre-soldered leads making laboratory manufacturing of the DART gages much simpler. The M-Bond 200™ bonding agent with excellent characteristics over a large portion of the range of temperatures of interest of asphalt binder testing (-40 °F to 275 °F) was employed to attach the strain gages to the DART gage. An interesting observation noted in investigating the optimal techniques to affix strain gages was that marking the duomorph surface with lead-based markers causes a loss of charge from the areas with the markings leading to an undesirable increase in the amount of current drawn. Therefore, markings were made with a fine felt-tipped pen. A 16-guage single conductor lead was soldered on to each of the two electroded face of the duomorph to carry the electrical charge produced by the piezo-driving subassembly. A 16-guage multiconductor lead was used to electrically ground the duomorph.

Semiconductor strain gages were also experimented with for the low temperature tests to obtain a better strain output. However, the extremely delicate nature of these gages and their cost precluded their use in this research after an initial trial.

3.3 Piezo Grounding and Driving Issues

Only one face of the symmetric DART gages can be driven with respect to the other face which is grounded resulting is a gage design where only one-half of the net piezoelectric potential is being utilized. However, the difficulty in driving both faces simultaneously was that an independent ground source needed to be established. This was accomplished in Phase II by introducing a small grounding tab as shown in Figure 14 to gain access to the central metallic shim which was to be grounded. The tab is cut in a triangular shape and is sized to
have just enough space to help make an electrical ground connection. The piezoceramic material on either sides of the tab was filed until the central metallic shim was exposed. A fine lead was soldered on to this metallic tab and was used to provide an access point for the required electrical ground. The advantage of grounding the gage with the help of the tab was that it allows both sides of the gage to be driven simultaneously to produce higher deflections for a given input voltage when compared to a DART gage whose piezoelectric faces are driven with respect to each other.

Figure 14. Duomorph gage showing details of grounding tab and lead connections.

Although the tab shown in Figure 13 introduces some asymmetry in the gage geometry, the tab dimensions were small enough to prevent it from being considered as an axisymmetric solid of revolution for analysis purposes. Figure 14 presents a sketch of an asymmetric DART gage with the grounding tab, strain gage, and lead connections.

Further modifications to the design in Phase II included arranging the piezoelectric layers with their poling axes asymmetrically placed about the neutral axis. This arrangement allows the both the faces of the duomorph to be driven simultaneously with a voltage signal of like polarity effectively doubling the strain output.

Figure 15 presents photographs of several DART gages assembled in this study including DART #2A, DART #2B, DART #3A.
3.4 The Electronic Subsystem

3.4.1 Signal Conditioning and Amplification

An important component of the DART assembly is the signal conditioning and amplification. This is the bulkiest of all components assembled in the prototype. At the lower temperatures, the strain output from the DART gage is very small and requires amplification of up to x2000 for the given driving voltages and sensitivities of the strain gages used. A Measurements Group® Vishay 2000 unit provided the necessary signal amplification. The Vishay unit, which has two internal 350-ohm resistance gages, completes the Wheatstone bridge circuit along with the two strain gages affixed to the DART gage. Both quarter- and half-bridge circuits were tested. The bridge excitation was varied from 10 to 15 VDC to determine the optimal value for the various asphalt stiffnesses considered.
3.4.2 Test Control and Data Acquisition Hardware

The electronic sub-system consisted of a personal computer equipped with a 16 channel, National Instruments AT-MIO-16E-2 analog-to-digital converter (ADC) board. The functions of the computer and board included the following:

- Generating the drive signal that produces deformations in the DART gage.
- Conditioning the strain gage signals from the DART gage as it deflects into a form that can be converted to digital values.
- Converting the conditioned sensor signals to digital values.

A precision external piezo linear amplifier was used to amplify the voltage signal from the ADC board for driving the DART gage. The peak current requirements of piezo actuator was determined using equation 5 and tabulated in Table 4. As can be noted from the table, the current requirements to drive the actuator are under 1 milliamp for a majority of the configured DART gages and less than 4 milliamps for the largest diameter gage assembled. The amplifier chosen could easily supply the peak voltage and current over the desired actuation frequency range. Overall, the combination of the test control and data acquisition hardware helped produce a digitally controlled signal with precise control.

\[
I_p = 2 \pi f C V_p \quad \text{Eq. (5)}
\]

where,

- \(I_p\) = Peak current, Amperes.
- \(f\) is the maximum operating frequency, Hz
- \(C\) is the capacitance of the piezo device, Farads
- \(V_p\) is maximum peak voltage required by the piezo actuator, Volts

Assuming a maximum operating frequency of 100 Hz (the upper end for asphalt binder testing at any temperature level) and peak driving voltage of 35 Volts (less than the conservative manufacturer recommendation for bipolar voltage of ±90 volts for a 7.5 mil
(19.3 mm) thick single sheet of PSI-5A), the current requirements of the various DART gages assembled (see Table 3) are shown in Table 4.

Table 4. Peak piezo actuator current requirements of the various DART gages assembled.

<table>
<thead>
<tr>
<th>DART Gage Name</th>
<th>PZT Sheet Thickness, t, mils</th>
<th>Disk Diameter, d, inch</th>
<th>Piezoelectric Disk Capacitance, nF</th>
<th>V&lt;sub&gt;peaks&lt;/sub&gt;, V</th>
<th>f, Hz</th>
<th>I&lt;sub&gt;peak&lt;/sub&gt;, milliamps</th>
</tr>
</thead>
<tbody>
<tr>
<td>DART # 1A</td>
<td>7.5</td>
<td>1</td>
<td>42.3</td>
<td>35</td>
<td>100</td>
<td>0.93</td>
</tr>
<tr>
<td>DART # 1B</td>
<td>7.5</td>
<td>0.75</td>
<td>23.8</td>
<td>35</td>
<td>100</td>
<td>0.52</td>
</tr>
<tr>
<td>DART # 1C</td>
<td>7.5</td>
<td>0.5</td>
<td>10.6</td>
<td>35</td>
<td>100</td>
<td>0.23</td>
</tr>
<tr>
<td>DART # 2A</td>
<td>7.5</td>
<td>1</td>
<td>42.3</td>
<td>35</td>
<td>100</td>
<td>0.93</td>
</tr>
<tr>
<td>DART # 2B</td>
<td>7.5</td>
<td>0.75</td>
<td>23.8</td>
<td>35</td>
<td>100</td>
<td>0.52</td>
</tr>
<tr>
<td>DART # 2C</td>
<td>7.5</td>
<td>0.5</td>
<td>10.6</td>
<td>35</td>
<td>100</td>
<td>0.23</td>
</tr>
<tr>
<td>DART # 3A</td>
<td>7.5</td>
<td>2</td>
<td>169.3</td>
<td>35</td>
<td>100</td>
<td>3.72</td>
</tr>
<tr>
<td>DART # 3B</td>
<td>7.5</td>
<td>1</td>
<td>42.3</td>
<td>35</td>
<td>100</td>
<td>0.93</td>
</tr>
<tr>
<td>DART # 3C</td>
<td>7.5</td>
<td>0.75</td>
<td>23.8</td>
<td>35</td>
<td>100</td>
<td>0.52</td>
</tr>
<tr>
<td>DART # 4A</td>
<td>7.5</td>
<td>1</td>
<td>42.3</td>
<td>35</td>
<td>100</td>
<td>0.93</td>
</tr>
<tr>
<td>DART # 4B</td>
<td>7.5</td>
<td>0.75</td>
<td>23.8</td>
<td>35</td>
<td>100</td>
<td>0.52</td>
</tr>
<tr>
<td>DART # 5A</td>
<td>7.5</td>
<td>0.78</td>
<td>25.8</td>
<td>35</td>
<td>100</td>
<td>0.57</td>
</tr>
<tr>
<td>DART # 6A</td>
<td>7.5</td>
<td>1</td>
<td>42.3</td>
<td>35</td>
<td>100</td>
<td>0.93</td>
</tr>
<tr>
<td>ADART # 1</td>
<td>7.5</td>
<td>1</td>
<td>42.3</td>
<td>35</td>
<td>100</td>
<td>0.93</td>
</tr>
<tr>
<td>ADART # 1B</td>
<td>7.5</td>
<td>1</td>
<td>42.3</td>
<td>35</td>
<td>100</td>
<td>0.93</td>
</tr>
<tr>
<td>ADART # 1C</td>
<td>7.5</td>
<td>1</td>
<td>42.3</td>
<td>35</td>
<td>100</td>
<td>0.93</td>
</tr>
<tr>
<td>ADART # B2</td>
<td>7.5</td>
<td>0.76</td>
<td>24.5</td>
<td>35</td>
<td>100</td>
<td>0.54</td>
</tr>
</tbody>
</table>

1 mil = 0.0254mm; 1 in = 25.4 mm

Note 1: The capacitance C was computed in accordance with equation (6):

\[ C = (d^2 \times K^T) / (5.67 \times t) \]

\[ Eq. (6) \]

\[ K^T \] for the PZT 5A material in the poling direction is assumed to be 1800 (see Table 2).

### 3.4.3 Test Control and Data Acquisition Software

Several “virtual instruments” or VIs were developed using the National Instruments LabVIEW software to both drive the DART gage and to store the resulting input and output waveforms in a spreadsheet format. The VIs developed included the following:

- Test actuation VI—to simulate the sinusoidal waveform, its frequency, and amplitude to actuate the load pulse.
- Data acquisition VIs
To acquire temperature and strain outputs data from sensor attached to the DART.

- Data analysis
  - VI to filter the signal.
  - VI to analyze the signal—signal amplitude.
- VI to store the data.

Peak strains and lag between the input and output signals—the desired inputs to the data reduction scheme to be discussed later—could be derived from the data thus stored and further processed to obtain the test parameters of interest.

Figure 16 illustrates the schematic arrangement of the components necessary to establish a fully functional DART system.

![Figure 16. Typical DART setup.](image)
3.5 Laboratory Evaluation of the DART Gage

3.5.1 Calibration of the Gage Response—Testing in Air

Initial evaluation of the DART gages comprised of testing them in air at various driving voltages, frequencies, and temperatures to achieve two objectives; (a) to determine gage behavior at various test frequencies around the range of frequencies of interest to asphalt binder testing and (c) to provide calibration reference for subsequent asphalt testing.

As testing progresses, the gages were tested at several AC voltage levels ranging from 35 V to 120 V\textsubscript{p-p}. At a given drive voltage level, all gages were tested at the frequency ranges of interest to asphalt testing, i.e., 0.5 to 30 Hz. Many gages were tested well beyond this range at frequencies of up to 2000 Hz. The ratio of strain gage output voltages, V\textsubscript{out}, to the driving voltage, V\textsubscript{in}, at each of the test frequencies for several gages is plotted against test frequency in Figure 17. All readings in the figure were taken at room temperature (approximately 22 °C or 72°F). The voltage ratio in the figure can be thought of in equivalent mechanical terms as the realized moment at the center of the disk to an applied external moment. Therefore, in the figure, the gage that has the lowest voltage ratio is the one that offers the least amount of flexural strain for an applied unit force. The following observations can be made from the figure:

- Among the Phase I gages—DART #1A, #2A, #3A, #3B, and #3C—for which data is plotted, the flexural rigidity gradually decreases. DART #1A has the highest rigidity followed by DART gages #2A and #6A and DART gages #3A through #3C in that order (see Table 3). Unsurprisingly therefore, the gage with the highest flexural rigidity (DART#1A), has the lowest voltage or moment ratio and vice versa.

- Although theoretically DART gages #4A and 4B have the same flexural rigidities as gages #3A through #3C and gages ADART #1 and ADART #B2 have the same rigidities as gages DART #2A through #2C, these Phase II gages were asymmetrically poled and both PZT layers were driven with respect to the grounded center metallic shim. Such an arrangement is intended to increase
(double) the output from the same applied input. Figure 17 confirms this expectation.

- Gage ADART #B2 which has the lowest flexural rigidity of all gages (roughly 3.5 times lower than gage #2B), also exhibits the highest voltage or moment ratio (approximately 3.5 times).
- For all gages, the voltage ratio was essentially flat as the test frequency increased.

![Graph showing output-to-input ratios for different gages.](image)

Figure 17. Ratios of peak-to-peak strain gage voltage output and DART gage input drive voltage from several DART gages tested in air.

Data from some gages were noted in Table 3 were not plotted due to a variety of reasons including gage malfunction or data collection errors. The only exception was DART #5A. Recall that this gage had the least flexural rigidity since it has no metal backing. Therefore, as expected, the gage produced the maximum output voltage per unit of drive voltage (i.e., the highest voltage ratio). Figure 18 presents a comparison the output-to-input ratios for DART #2B (symmetrically driven gage), ADART #1 (asymmetrically driven gage) both of which has metallic shims and DART #5A which has no shim. Clearly, DART #5A had the highest voltage ratio.
Figure 18. Comparison of output-to-input voltage ratios of DART gages with and without metallic shim.

Figure 19 presents the best-fit curves through the voltage ratio versus frequency response of the DART #2B gage well beyond the operating range of interest to asphalt binder testing. The intent was to identify gage characteristics at higher frequencies. The following observations can be made from the figure:

- It is apparent that the magnitude of driving voltage does not affect the $V_{out}$ to $V_{in}$ ratio significantly. This demonstrates that the gage has a linear response within the voltage range of interest.
- The gage output is essentially flat until about 100 Hz and subsequently increases with further increase in test frequency.
- It was also clear from the testing that the resonant frequencies of the gages operating in air were well above the frequency range of interest to asphalt testing, i.e., up to 30 Hz.
The behavior exhibited by the DART #2B gage was typical of all the DART gages tested. The flat voltage response was also found to be true over the entire temperature range of interest to asphalt binder testing. Figure 20 presents an example of the voltage ratio versus frequency for ADART #1 gage at different test temperatures. Another observation from the figure is that the test temperature does not appear to affect the gage behavior in air.

Figure 21 shows the phase shift angle (expressed in degrees) between the drive voltage and the strain response from the various DART gages assembled at various testing frequencies. The figure illustrates that for several of the gages, there is a strong dependence of phase shift on the frequency of testing for some gages. This finding establishes the need for establishing reference calibration data for each gage at each test frequency by testing them in air prior to testing asphalt binders with them.
Figure 20. Voltage ratios for ADART #1 gage tested in air at various temperatures.

Figure 21. Phase lag between input drive voltage and DART gage strain response from several DART gages tested in air.
Figure 22 presents the variation of phase shift with temperature for ADART #1 tested in air. While this figure shows a strong dependence of phase shift on frequency of testing for this gage, it shows a weak dependence of this parameter on the temperature of testing when the DART gage in air.

![Phase Shift vs Temperature](image)

Figure 22. Phase shift angles for ADART #1 gage tested in air at various temperatures.

### 3.5.2 Asphalt Binder Testing

#### 3.5.2.1 Phase I Proof-of-Concept Testing – Unaged Asphalt

Because the first expected use of the DART gage as a QA test device will be for unaged (or tank) asphalt binders, initial evaluation of suitability was conducted on an AC-20 tank asphalt. This asphalt was chosen because it was extensively evaluated for SHRP specification compliance in an earlier study at the University of Illinois and because its penetration, viscosity and Superpave binder properties are known. A cylindrical asphalt specimen with a height and diameter of 4 inch (101.6 mm) was prepared. Each DART gage was inserted into this specimen by turn in a manner that they were centered in the asphalt specimen to carry out the testing. Care was taken when embedding each gage to locate it centrally in the
specimen and as far away from the walls of the container holding the asphalt specimen as possible. This was done to ensure that the specimen size requirements of the original theoretical data reduction procedure developed by Briar et al. (1976) were not violated. Each gage was lowered into the asphalt binder after heating it sufficiently (in the range of 140°C or 284 °F) to allow the gages to be emplaced. The gages were held in position thereafter through mechanical restraints to ensure position integrity. Initial attempts at securing the initial position of the gage and its position during testing in the asphalt binder were done using crude laboratory contraptions. However, as testing progressed, a guide sleeve manufactured from a metallic channel section was developed to more accurately achieve this goal. The bottom of guide sleeve rests on the bottom of the container holding the asphalt specimen and the DART gages were positioned as shown in Figure 23. In addition to facilitating gage placement, the sleeve also helps avoid hauling the gage out of the asphalt specimen without pulling directly on the lead wires attached to the gages.

Figure 23. DART gage embedment with the help of a guide channel.

Gage responses in the asphalt medium were collected at the same frequencies and driving voltages at which the air tests were performed, i.e., a calibration test in air always preceded testing in the asphalt specimen. Asphalt binder temperature was varied over a wide range—approximately -10°C (14°F) to 60 °C (140°F). Temperature control was established by placing the asphalt specimen in a digitally controlled water bath. After testing was complete, the asphalt specimen was reheated to 60 °C (140°F) to allow easy removal and cleaning of the embedded DART gages.
Figure 24 presents the non-dimensional voltage output of the DART #2B symmetrically poled gage (driven on one side) when tested across a range of frequencies and temperatures in an unaged asphalt binder bearing a viscosity grade of AC-20. The non-dimensional voltage was determined in accordance with equation 7:

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \left( \frac{V_{\text{out}}^{\text{AC}}}{A_{\text{AC}} * V_{\text{in}}^{\text{AC}}} \right) \left( \frac{V_{\text{out}}^{\text{air}}}{A_{\text{air}} * V_{\text{in}}^{\text{air}}} \right)
\]

Eq. (7)

where,

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \text{Non-dimensional output voltage.}
\]

\[
V_{\text{out}}^{\text{AC}} = \text{Output of strain gage affixed to a DART gage embedded in asphalt, V.}
\]

\[
A_{\text{AC}} = \text{Applied gain to a strain gage affixed to a DART gage embedded in asphalt.}
\]

\[
V_{\text{in}}^{\text{AC}} = \text{Drive voltage applied to a DART gage embedded in asphalt, V.}
\]

\[
V_{\text{out}}^{\text{air}} = \text{Output of strain gage affixed to a DART gage operated in air, V.}
\]

\[
A_{\text{air}} = \text{Applied gain to a strain gage affixed to a DART gage operated in air.}
\]

\[
V_{\text{in}}^{\text{air}} = \text{Drive voltage applied to a DART gage operated in air, V.}
\]

Figure 24. Non-dimensional voltage output of DART #2B (0.75 in or 19.3 mm diameter 20 mil or 0.51 mm thick) gage in air and in an unaged AC-20 asphalt binder.
The test data for the same gage when tested in air just prior to testing the asphalt binder are also plotted in the figure. It is apparent from the figure that the DART #2B gage output is sensitive to the asphalt binder stiffness with the stiffer binders causing a lower non-dimensional voltage output (and hence strain) and vice versa at any given frequency. Also, along expected lines, the gage output decreases as the test frequency increases. Further, as the test temperature goes from low to high, the gage output increases approaching the unconstrained value established by testing it in air. Specifically, as binder temperature approaches 60°C (140°F), the gage behaves as if it is in air thus, i.e., loses sensitivity to the surrounding asphalt binder. In practical terms, this empirically establishes the limiting lower binder stiffness over which this gage is useful.

Figure 25 presents the phase shift between the strain gage and drive signals of the DART #2B gage when tested in the unaged AC-20 asphalt specimen. As can be noted, the phase shift expectedly decreases as the asphalt binder temperature (and, therefore, stiffness) decreases at any given test frequency. As the test frequency increases, the phase shift increases. As with the gage’s output voltage, the phase shift, when tested in asphalt approach the corresponding test values in air as the test temperature approaches 60°C (140°F). Figure 25 and Figure 24 establish the ability of the DART system to “fingerprint” an asphalt binder over a range of temperatures and frequencies.

Figure 26 and Figure 27 present the fingerprint parameters—non-dimensional voltages and phase shift angles—for DART #3A gage. This gage has a diameter of 2 inches and is thinner by 1 mil compared to the DART #2B gage. The overall flexural rigidity of this gage is approximately 18.5 percent lower than the DART #2B gage and it is the largest diameter gage assembled in this study.

This gage was specifically constructed to increase sensitivity at elevated temperatures. The data presented confirms the earlier trends observed with the DART #2B gage with regard to the sensitivity to temperature and frequency of testing. As expected, lowering the gage flexural rigidity seemed to have produced the desired effect of increasing the gage sensitivity at the higher test temperatures, e.g., 60 °C (140°F) when compared to the DART #2B gages.
Figure 25. Phase shift between the strain gage and drive signals of DART #2B (0.75 inch or 19.3 mm diameter, 20 mil or 0.51 mm thick) gage in air and in an unaged AC-20 binder.

Figure 26. Non-dimensional voltage output of DART #3A (2 inch or 50.8 mm diameter, 19 mil or 0.48 mm thick) gage in air and in an unaged AC-20 binder.
Figure 27. Phase shift between the strain and drive signals of DART #3A (2 inch or 50.8 mm diameter, 19 mil or 0.48 mm thick) gage in air and in an AC-20 unaged AC-20 binder.

Moreover, voltage outputs of the DART #3A gage over the frequency range of testing were more distinct from the response of the gage in air when compared to DART #2B gage primarily due to the lower rigidity of the gage. This experiment confirmed the notion that matching the stiffness of the gage to the stiffness of the test medium is needed to produce satisfactory results across the stiffness ranges of interest to binder testing. In their theoretical analysis, Briar et al. (1976) contended that matching the gage and medium stiffness in this way might lead to better resolution of data at all stiffness ranges of interest.

A shimless gage—DART #5A—was manufactured to further explore the possibility of testing the softer binders with a softer gage. The DART #5A gage had the lowest flexural rigidity of all gages tested. One of the PZT layers was driven with respect to the other layer. Some operational difficulties were anticipated with this gage due to potential for developing stress singularities at the interface of the PZT layers. However, the gage was experimented with for completeness of the research effort. The experimental work showed that, just like with the other gages tested, even the shimless gage also appeared to lose sensitivity at the
warmer asphalt binder temperatures. As expected, due to its lower flexural rigidity, the voltage output from this gage was an order of magnitude higher than DART #2B and DART #3A. However, the outputs obtained from this gage did not appear to smoothly transition from one temperature to the next as with the other gages possibly due to the presence of singularities at the PZT layer interface. Some gage repeatability and data acquisition issues were also observed when working with this gage. Attempts to collect more data from this gage proved unfruitful because the fragile nature of this gage led it to fail after one cycle of testing. The gage was deemed not to be operationally rugged for asphalt testing and was ruled out from further evaluation thus establishing a limiting value to the gage stiffness ranges that could be experimented with to ensure ruggedness and repeatability of the DART.

3.5.2.2 Phase I Proof-of-Concept Testing – Aged Asphalt Specimen

Accelerated Aging of tank AC-20 asphalt binder was performed using the PAV in accordance with the AASHTO R 28 protocol. The PAV residue was then tested using the DART gages and the DSR at various frequencies and temperatures. The PAV sample was placed in a cylindrical container with a height and diameter of 2 inches. A smaller specimen sample was used due to production difficulties associated with obtaining a 4 inch diameter sample for the PAV residue. It was recognized at the outset that the stiffer nature of the aged binder (analogous to colder temperatures or higher frequencies of testing) would need higher driving voltages to obtain clean, noise free strain gage outputs from the DART. Because earlier tests of the unaged binder demonstrated that the magnitude of the driving voltage does not affect the output modulus, a peak-to-peak AC voltage of \( +70 \text{ V}_{pp} \) was used for the PAV binder testing. This voltage level was well below the safe maximum AC drive voltage levels (180 \( \text{V}_{pp} \)) recommended by the manufacturer for the piezoelectric materials being used.

Figure 28 compares the non-dimensional output of the of the DART #2B gage when embedded in a PAV-aged asphalt binder specimen at 22°C (72°F) and 30°C (86°F). In the AASHTO M320 specification, the PAV residue is tested at estimated intermediate temperatures in this range to evaluate the asphalt binder’s fatigue resistance. It is clear from the figure that the gage output is much lower than the data from testing in air as well data obtained from the same gage at similar temperatures but from an unaged binder (see Figure
The strain levels are very low for the PAV aged binders from this operation (in the order of 0.001%). Higher drive voltages and a more sensitive gage were determined to be desirable.

![Graph](image)

Figure 28. Non-dimensional voltage output of DART #2B (0.75 inch or 19 mm diameter, 20 mil or 0.51 mm thick) gage in air and in a PAV aged AC-20 asphalt binder.

### 3.5.2.3 Phase II Testing

In the Phase II effort, investigations with the next generation gages with better gage production techniques were launched with an objective to standardize the gage operation across a wide range of temperatures. Ways to improve strain sensing at the lower temperatures were examined while the limiting higher test temperatures were determined.

For low temperature testing, it was decided that the best way to increase the gage output (more gage deflection and hence strain per unit of drive voltage) was to drive both sides of the DART gage simultaneously (in Phase I only one side of the DART gage was driven with respect to other side which was electrically grounded). When both sides are driven, the power requirements increase due to the 4:1 reduction in the electrical impedance. However,
this increase in power requirements to drive both the disks simultaneously was not considered a significant drawback since, as shown in Table 4, the gages draw very low current even at the upper end of frequencies of interest to asphalt binder testing.

To drive both faces of a DART gage, an asymmetric or parallel poled PZT material was necessary. To accomplish this, the polarity of one of the PZT layers in the Phase I DART gage stock sandwich material which were originally series poled, was reversed in the laboratory. Parallel poled circular gages were then manufactured from this stock material.

Figure 29 and Figure 30 respectively present the non-dimensional voltages and phase shifts for DART #4A gage. This gage has a diameter of 1 inch and has the same individual layer and overall thicknesses (and hence flexural rigidity) as DART #3A. The data presented confirms the earlier trends observed with regard to the sensitivity and usefulness of the gages over a range of asphalt stiffneses. Note that DART #4A gage was tested in colder temperatures. The voltage outputs of the DART #4A gage were clearly superior when compared to all other gages tested. This is a useful property particularly for stiff asphalt binders (e.g., aged or modified asphalt), colder test temperatures or higher frequencies of testing. The higher outputs from the gage are primarily attributed to driving both PZT layers in the sandwich assembly. Thus this gage is considered to be more useful for intermediate to cold temperatures prescribed in the AASHTO M320 specification. The sensitivity of the gage at the higher temperatures remained the same as all other gages tested in this study with the exception of the DART #3A gage which had superior high temperature sensitivity.
Figure 29. Non-dimensional voltage output of DART #4A (1 inch or 25.4 mm diameter, 19 mil or 0.48 mm thick) gage in air and in an unaged AC-20 asphalt binder.

Figure 30. Phase shift between the strain and drive signals of DART #4A (1 inch or 25.4 mm diameter, 19 mil or 0.48 mm thick) gage in air and in an AC-20 unaged AC-20 binder.
Encouraged by the findings of the DART #4A gage, commercial stock piezoelectric sandwich materials that were parallel poled were procured from the manufacturer and circular DART gages were manufactured from this stock. At the same time, to improve gage durability, strain gages with pre-soldered leads were also procured and affixed to the gages to improve production efficiency of the gages and minimize errors. Two types of asymmetric gages were manufactured from the new stock or raw material – one with a steel metal shim and a higher flexural rigidity and the other with a brass backing with a lower rigidity. Three gages—ADART #1, #1B, and #1C—had the steel shim backing and were all 1 inch in diameter and had the same dimensions and flexural rigidities. Gage ADART #B2 was made of a thinner PZT wafer than the other asymmetric gages and also had a brass backing. It was also 1 inch in diameter but had a 56 percent lower flexural rigidity than the ADART #1 series. These gages were driven at a much higher AC voltage level (120 V_p-p) in order to further increase the quality of the signal at intermediate and cold temperatures. The manufacturer limitation on the maximum drive voltage for the materials employed in this study was 180 V_p-p.

While all the asymmetrically gages produced consistent results when tested in asphalt across a range of temperatures and frequencies, the ADART #1 series gages performed better than the ADART #B2 series in terms of repeatability and reproducibility of the signal. The testing qualitatively confirmed that the DART gages can be used to determine time and temperature sensitive properties of various asphalt binders. Figure 31 presents the non-dimensional voltage ratio of the ADART #1C gage when excited at 1.59 Hz in four different asphalt binders over a range of temperatures. It can be noted that from the figure that the AC-10 binder being the least stiff binder offers the highest voltage ratio at any temperature. On the other hand, the AC-20 PAV aged binder being the stiffest offers the lowest voltage ratio. The AC-20 and Pen 40/50 fall in between and rank proportional to their laboratory tested stiffnesses. This plot offers another insight into the usability of the DART to perform fingerprint analysis of binders for field QA use.

Figure 32 presents the response of the ADART #1C gage embedded in an unaged AC-20 asphalt binder at various temperatures. Due to the improved drive efficiency and increased
input drive voltage, this gage offers the highest non-dimensional voltage ratio at both the low and high temperatures.

Figure 31. Fingerprint of various asphalt binders with the ADART #1C gage operated at 1.59 Hz.

Figure 32. Response of the ADART #1C gage in an unaged AC-20 asphalt binder at various temperatures when operated at 1.59 Hz.
One of the indicators of the efficiency of a gage used in this study was the non-dimensionalized voltage ratio. Figure 33 presents a comparison of the non-dimensional voltage ratios for various gage types studied herein when tested in air. Gages with higher non-dimensional voltage ratios are desirable because they produce a better quality signal and are able to exercise the asphalt specimen into which they are embedded more strongly not only facilitating more precise data acquisition but also ensuring that the gages can be used over a wide range of asphalt stiffnesses. Contrasting the data in Figure 33 with Table 3 it can be noted that, as expected, the non-dimensional voltage ratios, for the most part, are inversely proportional to their flexural rigidities. Higher the flexural rigidity of the gage, the lower the gage’s output and vice versa. An additional variable in the form of number of gage faces driven simultaneously is needed to explain the variability in voltage ratios for gages with similar rigidities. For example, DART # 3A and DART #4A have similar flexural rigidities but the latter produces a better output signal. The primary reason is because both PZT layers of the gage are driven simultaneously in the latter while only one PZT layer is driven in the former. Driving both faces simultaneously effectively doubles the strain output which explains why all the asymmetrically poled gages have higher non-dimensional voltage ratios compared to the symmetrically poled gages.

Of the gages for which data is reported in Figure 33, the maximum strain during calibration testing in air was recorded for the ADART #1C gage which had a strain output of 132 microstrains at 1.59 Hz. When testing asphalt binders, a useful parameter to examine the sensitivity of a gage to the asphalt binder it is embedded in is to examine the ratio of the strains in air and in asphalt. According to Briar et al. (1976), this parameter is useful in determining the stiffness and phase angle of the surrounding viscoelastic medium. Figure 34 presents this parameter for the various DART gages tested in unaged asphalt binder. Note that to compute the strain ratio plotted in the figure, the testing in air and in asphalt were performed usually within the same week. It was later discovered that performing the testing within the same day might lead to less variability in computing this parameter and minimized the effects of temperature, electronics, and power fluctuations. Nevertheless, the following important observations can be made from the figure:
Figure 33. Comparison of non-dimensionalized disk outputs of various DART gages operating at room temperature (22°C or 72°F) in air.

Figure 34. Strain ratios of various DART gages tested in unaged asphalt binder at a frequency of 1.59 Hz.
• Though the gage actuation parameters and gage outputs from DART gages #2B, #3C, and #4A were different, they show similar strain ratio versus test temperature relationships. Therefore, their ability to sense the changes in properties of the asphalt binder into which they are embedded can be considered to be similar. All these gages perform satisfactorily up to a test temperature level of 40 to 45 °C (104 to 113°F) exhibiting a gradual increase in strain ratio with test temperature. At higher temperatures, the strain ratios asymptotically approach a value of 1.0 (implying that the strain in the asphalt specimen is the same as that in air). The data collection errors at the higher temperatures also increase with some gages reporting a strain ratio greater than 1.0.

• Due to their lower rigidity, DART #3A and ADART #B2 exhibit a flatter slope the remainder of the gages and are more sensitive to the asphalt binder stiffness changes at higher temperatures. However, these have a relatively low strain ratio at the lower test temperatures (or higher asphalt stiffnesses) thus making them less applicable for cold temperature testing (or testing stiffer binders).

Figure 35 presents the strain ratio versus temperature plot for the ADART #1C gage. The curves shown in the figure are for different asphalt binders. Clearly, the softer asphalt produces a plot with a higher slope than the harder asphalts. The strain ratio approaches a value of unity much quicker for the softer binders when compared to stiffer asphalts. Such plots carried out over a range of frequencies can be useful in field acceptance of asphalt binder material.

To generalize the findings from Figure 34 and Figure 35, the strain ratios were plotted as a function of a non-dimensional stiffness parameter, M’. This quantity represents the ratio of the asphalt binder and DART gage stiffness and is determined using equation 8 taken from Briar et al. (1976).
Figure 35. Strain ratio signatures of the ADART #1C gage tested in various unaged and aged asphalt binders at a frequency of 1.59 Hz.

$$M' = \frac{E' a^3}{D}$$  \hspace{1cm} \text{Eq. (8)}

where,

- $M'$ = Asphalt binder-to-Gage Non-dimensional stiffness.
- $a$ = radius of the DART gage, psi.
- $E'$ = real part of the complex modulus of asphalt, psi.
- $D$ = flexural rigidity of the DART gage, lbf-in (see equation [4]).

Figure 36 presents the strain ratio versus $M'$ plots for various DART gages when embedded in the AC-20 binder. Rather than empirically determining the test temperatures over which each gage is effective, this plot allows one to determine the allowable non-dimensional stiffness ratios to obtain desirable strain ratios, i.e., strain ranges that can be collected effectively and efficiently collected with the DART. Once this is determined, the gage radius and rigidity can be varied to obtain a valid gage for a given asphalt binder stiffness range of interest.
Figure 36. Strain ratios of various DART gages tested in unaged AC-20 asphalt binder at a frequency of 1.59 Hz plotted against non-dimensional stiffness.

Figure 37 presents plots of the strain ratio versus the non-dimensional stiffness parameter for the ADART #1C gage tested in different unaged and aged binders. Clearly, this plot illustrates that the ADART #1C gage produces high quality outputs enabling testing of various binders over a range of asphalt-to-gage stiffness ratios.

For a given DART gage, as the asphalt binder gets softer, e.g., either due to elevated test temperatures or testing at lower frequencies, $M'$ decreases and vice versa. In general, matching the stiffnesses of the DART gage and the surrounding asphalt binder to produce a gradual slope of the strain ratio-$M'$ curve would result in a more discriminating and accurate measurement environment. Avoiding strain ratios close to 1.0 and below 0.01 would avoid extreme $M'$ values and associated data gathering errors. Experimentally it was determined that most gages tested in this study lose sensitivity to the asphalt binder when the strain ratios approach values of 0.9. On the lower end, strain ratios below 0.01 result in extremely small strain readings of the DART gage when embedded in asphalt (less than 1 micro strain) increasing the potential for measurement error. If these values of strain ratios are considered
to provide the upper and lower bounds of the acceptable range of desirable outputs from the gages, then the corresponding $M'$ parameters can be determined for the various DART gages from Figure 36 and Figure 37.

Figure 37. Strain ratio signatures of the ADART #1C gage tested in various unaged and aged asphalt binders at a frequency of 1.59 Hz.

Figure 38 presents ranges of $M'$ over which the various DART gages tested in this study provide good quality strain outputs when embedded in an AC-20 asphalt binder. The wider the range of $M'$ over which a good quality signal is produced and the more evenly the gage performs on either side of $M' = 1$, the better the gage is able to detect the properties of the asphalt binder in which it is embedded. It is apparent from the figure that both the DART #3A (a large diameter Phase I gage) and ADART #1C gage (a Phase II gage with a more refined electronic subsystem and gage actuation options) provide good quality of outputs over a wide range of asphalt stiffnesses (over 5 decades). However, while the ADART #1C gage has very little bias with respect to the $M'$ value of unity, the ADART #3A gage provides good quality outputs mostly when its $M'$ value is greater than unity indicating that it performs better when the stiffness of the asphalt it is embedded in greater than its own.
flexural rigidity. Moreover, the DART #3A gage is 2 inches in diameter which is disadvantageous when working with aged binders since the sample size requirements are larger for large gages to ensure that the boundary effects do not affect the gage outputs. Therefore, of all the gages assembled in this study, the ADART #1C is a gage that can be considered to offer the most potential to test asphalt binders. The gage with the next widest M’ range of operation was the ADART 1 gage which provided good quality strain outputs over 4 decades of asphalt stiffness with a bias towards operating better in stiffer asphalts.

Figure 38. Ranges of M’ over which the various DART gages provide good quality strain outputs over a range of asphalt stiffnesses.

Focusing on the ADART #1C gage which had the most favorable single gage performance and size and operating parameters (asymmetrically poled gage with high strain outputs), the findings of Figure 38 can be used to establish the ranges of asphalt binder stiffness over which the DART can be expected to perform well. This can be done with the help of
equation 8. Rearranging the equation, the real part of binder’s complex shear modulus, $G’$, can be expressed approximately as:

$$G’ = \frac{E’}{2(1 + \nu)} = \frac{D M’}{a^3}$$  \hspace{1cm} \text{Eq. (9)}

where,

- $E’$ = real part of the complex modulus of asphalt, psi.
- $\nu$ = Poisson’s ratio of asphalt binder taken to be 0.5.
- $M’$ = Asphalt binder-to-Gage Non-dimensional stiffness.
- $a$ = radius of the DART gage, psi.
- $D$ = flexural rigidity of the DART gage, lbf-in (see equation [4]).

Using known low and high values of $M’$ (0.004 and 231, respectively) along with $D$ and $a$ of the ADART #1C gage, the range of $G’$ over which the gage can be effective when the binder stiffness is estimated to be 0.1 psi (0.69 kPa) to 4250 psi (29 MPa). This captures a majority of neat, modified, aged and unaged binders tested by the DSR.

### 3.6 Repeatability and Potential Accuracy of the DART Output

The consistency with which DART gages can collect data was evaluated throughout the study. It should be noted that based on this evaluation, the range of strain ratios over which the gages can be expected to collect good data were established. Testing norms such as performing the testing in air and in asphalt as close to each other as possible and were also established. In addition, in this study, the ADART #1C gage was used to perform testing over a wide range of temperatures and frequencies. The repeatability of the gage output, i.e., the bending strain at the center of the gage and the signal shift, was studied both in air and in asphalt. The following testing sequence was followed when testing in asphalt:

Step 1: Heat the asphalt specimen to about 140°C (284°F) for about 5 minutes to allow the DART gage to be inserted.
Step 2: Insert the ADART #1C gage with the help of the guide channel into the asphalt specimen taking care that the gage is as close to the center of the specimen as possible.

Step 3: Place the specimen with the gage into a temperature control chamber.

Step 4: Bring the specimen to the desired test temperature and take 10 observations for each frequency of interest.

Step 5: Repeat step 4 for all test temperatures of interest.

The asphalt binder used for the repeatability experiment was the AC-20 binder. The test temperatures adopted were 5°C (41°F), 10°C (50°F), 20°C (68°F), 40°C (104°F), and 55°C (131°F). At each temperature, the asphalt specimen was tested at 0.1, 1, 1.59, 10, 30, and 100 Hz. This type of testing is aimed at characterizing the variability of the DART gage output during a single sitting of frequency and temperature sweep analysis of an asphalt binder. The primary source of variability in such a study is from the changes in electrical signals in the sensor electronics at a given test point. Table 5 and Table 6 summarize the findings of this study at a test frequency of 1.59 Hz for one set of observations.

Table 5. Repeatability analysis of bending strain output at the center of the DART gage at a test frequency of 1.59 Hz.

<table>
<thead>
<tr>
<th>Observation Number</th>
<th>Peak-to-Peak Gage Strain in Air, Volts</th>
<th>Gage Strain Output in Asphalt, Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5°C (41°F)</td>
<td>10°C (50°F)</td>
</tr>
<tr>
<td>1</td>
<td>7.75</td>
<td>0.270</td>
</tr>
<tr>
<td>2</td>
<td>7.75</td>
<td>0.270</td>
</tr>
<tr>
<td>3</td>
<td>7.75</td>
<td>0.270</td>
</tr>
<tr>
<td>4</td>
<td>7.75</td>
<td>0.281</td>
</tr>
<tr>
<td>5</td>
<td>7.525</td>
<td>0.274</td>
</tr>
<tr>
<td>6</td>
<td>7.75</td>
<td>0.272</td>
</tr>
<tr>
<td>7</td>
<td>7.75</td>
<td>0.274</td>
</tr>
<tr>
<td>8</td>
<td>7.75</td>
<td>0.278</td>
</tr>
<tr>
<td>9</td>
<td>7.75</td>
<td>0.270</td>
</tr>
<tr>
<td>10</td>
<td>7.75</td>
<td>0.268</td>
</tr>
<tr>
<td>Mean</td>
<td>7.728</td>
<td>0.274</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.071</td>
<td>0.004</td>
</tr>
<tr>
<td>COV</td>
<td>0.92%</td>
<td>1.44%</td>
</tr>
</tbody>
</table>
Table 6. Repeatability analysis of signal shift output at the center of the DART gage at a test frequency of 1.59 Hz.

<table>
<thead>
<tr>
<th>Observation Number</th>
<th>Signal Shift in Air, milliseconds (msec)</th>
<th>Gage Signal Shift Output in Asphalt, msec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5°C (41°F)</td>
<td>10°C (50°F)</td>
</tr>
<tr>
<td>1</td>
<td>28</td>
<td>394.9</td>
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<td>2</td>
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<tr>
<td>7</td>
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<td>390.9</td>
</tr>
<tr>
<td>8</td>
<td>28</td>
<td>396.9</td>
</tr>
<tr>
<td>9</td>
<td>28</td>
<td>394.9</td>
</tr>
<tr>
<td>10</td>
<td>28</td>
<td>394.9</td>
</tr>
<tr>
<td>Mean</td>
<td>27.8</td>
<td>393.5</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.063</td>
<td>2.67</td>
</tr>
<tr>
<td>COV</td>
<td>2.28%</td>
<td>0.68%</td>
</tr>
</tbody>
</table>

The mean coefficient of variation (COV) of the DART strain measurements in asphalt averaged over the entire range of test temperatures is 2.3 percent and the mean standard deviation is 0.072 V from Table 5. Likewise, the mean COV of the DART signal shift measurements is 3.1 percent and the mean standard deviation is 3.3 milliseconds from Table 6. The readings when the DART is operated in air are even more consistent as evidenced by the data in Table 5 and Table 6. It is clear from these findings that that the DART gage is capable of providing highly repeatable outputs.

Note that in the all the testing reported above, the DART gage, once embedded in the asphalt, remained there throughout. Further only one DART gage was used in testing. Therefore, the repeatability study above does not capture the effect of variability caused by factors such as:

- Daily variations in the electric signal used to drive the DART gage.
- Slight changes in dimensions (thicknesses and diameters) of the DART gages when they are manufactured from different lots of raw materials.
- Slight misalignment of strain gages.
- Change in DART gage characteristics with age.
- Off-center placement of the DART gage in the asphalt specimen.
All the factors noted above, with the exception of the last one, impact the strain response of the DART gage in air as well as in asphalt equally. Hence, the ratio of the strain in asphalt and in air (strain ratio) remains unaltered as long as both the readings are taken at closely spaced intervals. Recall that the strain ratio is the primary parameter of interest in the DART analysis. In general, it is recommended that the DART gage output in air be recorded just prior to starting a sequence of tests in asphalt to provide a calibration point.

Variability produced by misalignment of the DART gage with respect to the center of the specimen is however uncalibratable. The primary concern here is that if the gage gets too close to the walls of the container holding the asphalt specimen, the assumption made in the data reduction process that the gage is surrounded by significantly large amount of material on all sides is violated. The changed boundary conditions might lead to a response far different than what is expected. Although, the guide sleeve, with the help of which the DART gage is placed in the specimen, limits large-scale misalignments, it is worthwhile to study the variability associated with this factor. A limited testing program was therefore undertaken using the ADART#1C gage. A frequency of 1.59 Hz was used and the asphalt specimen was tested at two temperatures 20°C (68°F) and 55°C (131°F). At each temperature 5 observations of the gage response were collected. The DART gage was removed after and each observation and reinserted into the asphalt specimen before the next observation was taken all the time ensuring that the gage response is as close to the center of the specimen as possible. Although in reality it is highly unlikely and also undesirable to remove the gage between successive readings in a temperature sweep analysis, this experiment is aimed at simulating the variability associated with asphalt testing performed over several days on the same specimen. The results of this experiment are reported in Table 7.

The mean standard deviation and COV of the strain output for the two temperatures studied are 0.133 V and 2.67 percent, respectively. Likewise, the mean standard deviation and COV of the signal shift output are 2.74 msec and 4.58 percent, respectively. Note that the corresponding values from Table 5 for the strain output were 0.11 V and 2.3 percent and for the signal shift output from Table 6 were 2.25 msec and 3.1 percent, respectively.
Table 7. Repeatability analysis of bending strain and signal shift with repeated removal and reinsertion of the DART gage from the asphalt specimen.

<table>
<thead>
<tr>
<th>Obs. No.</th>
<th>Duomorph Strain Output in Asphalt, Volts</th>
<th>Duomorph Signal Shift Output in Asphalt, msec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Specimen Temp = 20°C (68°F)</td>
<td>Specimen Temp = 55°C (131°F)</td>
</tr>
<tr>
<td>1</td>
<td>3.656</td>
<td>7.688</td>
</tr>
<tr>
<td>2</td>
<td>3.560</td>
<td>7.400</td>
</tr>
<tr>
<td>3</td>
<td>3.452</td>
<td>7.625</td>
</tr>
<tr>
<td>4</td>
<td>3.650</td>
<td>7.635</td>
</tr>
<tr>
<td>5</td>
<td>3.340</td>
<td>7.325</td>
</tr>
<tr>
<td>Mean</td>
<td>3.532</td>
<td>7.535</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.121</td>
<td>0.144</td>
</tr>
<tr>
<td>COV</td>
<td>3.43</td>
<td>1.91</td>
</tr>
</tbody>
</table>

The combined variance of the DART tests for these two temperatures can therefore be determined using the sum of the individual variances as follows:

\[ \sigma_{combined}^2 = \sigma_{testing1}^2 + \sigma_{testing2}^2 \]  \hspace{1cm} Eq. (10)

The standard deviation can be determined by simply taking a square root of the variance. Using this approach, the standard deviation of the strain output after taking into account all possible forms of testing variability is 0.173 V. The standard deviation of the signal shift was estimated to be 3.55 msec. Both these estimates of variability are within acceptable ranges compared to the magnitude of the strain and signal shift mean outputs. Therefore it can be concluded that, under a single operator environment, the DART gage outputs are highly repeatable.

3.7 Asphalt Specimen Size and Gage Embedment

According to Briar et al (1976), when the DART gage is embedded at the center of a cube of asphalt material whose side length is greater than twice sensor diameter, edge effects on the strain response of the gage can be considered as being negligible. The main significance of this assumption is to ensure that their theoretical approach, which requires quiet boundaries that are not affected by the perturbation of the asphalt material caused by the DART gage, could be used for analyzing the gage outputs. Since the specimen used in the DART gage
testing of asphalt binders were cylindrical in nature, it was conjectured in this study that the specimen size in the direction of motion of the DART gage while it is in operation, has the most influence on its response due to the material perturbation in this direction. By extension, specimen size in the directions orthogonal to this direction of motion of the DART gage will not have a significant impact on the response. Based on these assumptions, cylindrical unaged asphalt specimens with a diameter at least twice the size of the DART gage and a height up to 4 inches were chosen for testing. For PAV aged samples, a cylinder of 2 inches was used due to the difficulty anticipated in processing the amount of asphalt required for a 4 inches high cylindrical PAV aged asphalt specimen. The gages were lowered into the heated asphalt binder vertically as shown in Figure 23 such that they were centrally located in the specimen.

As part of the proof-of-concept testing, it was decided to test the effects of inaccurate gage embedment on its strain outputs. All the testing was conducted in an unaged binder at different temperatures. Two gage positions were adopted for the testing:

- Normal gage placement. This condition satisfies the normative quite boundary requirements of Briar et al. (1976).
- Gage place 0.5 inch (12.5 mm) from the container wall.

All testing was performed using a cylindrical unaged Pen 40/50 asphalt specimen with a diameter and height of 4-inches, respectively. Figure 39 through Figure 42 present the non-dimensional voltage output of the DART gage as a function of the temperature of asphalt specimen when the gage is excited at 0.5 Hz, 1.59 Hz, 10 Hz, and 30 Hz, respectively. It is apparent from the figures that the position of the gage does not affect the gage’s non-dimensional voltage output at the test frequency of interest—1.59 Hz—or lower. However, as the test frequency increases, the position of the gage appears to affect the gage output particularly at the highest temperature considered in the study—40°C (104°F).
Figure 39. Non-dimensional voltage output of the DART gage at test frequency of 0.5 Hz.

Figure 40. Non-dimensional voltage output of the DART gage at a test frequency of 1.59 Hz.
Figure 41. Non-dimensional voltage output of the DART gage at a test frequency of 10 Hz.

Figure 42. Non-dimensional voltage output of the DART gage at a test frequency of 30 Hz.
Figure 43 through Figure 45 present the phase shift of the DART gage in asphalt as a function of the temperature of the asphalt specimen when the gage is excited at 1.59 Hz, 10 Hz, and 30 Hz, respectively. The phase shift appears to be unaffected by the position of the gage at any of the frequencies or temperatures considered for this experiment.

The experiment does confirm the assumption that the size of the asphalt specimen is a factor that could affect gage outputs when the specimen is tested over a wide range of frequencies and temperatures. However, when testing at lower frequencies, the size of the specimen is not a significant concern.

![Graph showing phase shift vs. test temperature.](image)

Figure 43. Phase shift of the DART gage at a test frequency of 1.59 Hz.
Figure 44. Phase shift of the DART gage at a test frequency of 10 Hz.

Figure 45. Phase shift of the DART gage at a test frequency of 30 Hz.
3.8 Summary of Findings and Conclusions

3.8.1 Summary and Findings

The focus of the effort described in this chapter was in the redevelopment of the DART gage to verify its suitability for asphalt binder testing. In phase I, the focus was on establishing the viability of the DART through a logical redevelopment of the “original” duomorph gage for application in asphalt rheology. Phase II dealt with a more comprehensive investigation resulting in the development of a prototype device.

The main experimental variables in phase I were the dimensions of the circular duomorph disks, instrumentation (including strain gage types and signal conditioning and amplification devices), methods employed for driving and grounding the duomorph gage, gage excitation voltages, and data reduction procedures. A user-friendly software interface was developed using the National Instruments software, LABVIEW, to facilitate gage excitation and data acquisition under this phase. The DART system that evolved at the end of phase I was the result of a continuous refinement process that spanned the entire length of the study and utilized the best methods and materials at the time. The feasibility of the system was evaluated by testing a reference asphalt binder at various temperatures, processing states (original versus PAV binder), frequencies, and strain levels. The raw data from the DART were examined, as part of the verification process, to investigate if the data agrees with engineering intuition. The following main conclusions were drawn from these investigations:

- Equipment has been assembled at a relatively low cost that shows considerable promise to test asphalt binders in accordance with the SHRP specifications.
- The DART gage and the associated electronics can withstand normal laboratory use for extended periods of time. This would suggest that it could also be used as a field acceptance device where the conditions are more severe.
- The bending strains and phase shifts measured from the DART gage were repeatable.
• Tests conducted on the DART gage in air show a linear effect of increasing the driving or excitation voltage on the bending strain response. Further, it was also determined that the response is essentially constant with driving frequency within the range of interest to asphalt binder testing.

• Initial verification of the raw data from the DART embedded in asphalt indicates that DART system is sensitive to changes in both the parameters of interest, i.e., modulus and phase angle. This suggests that the raw outputs of the gage—strain outputs and signal shift—can be used to verify if the binder delivered to the job-site is similar to that tested in the laboratory. A “fingerprint” of the asphalt binder being supplied to the job-site, in terms of raw DART gage response at a range of temperatures and frequencies—needs to be established at the supplier location. This fingerprint can then be verified at the plant or the job-site in a rapid manner using the DART for QA purposes thus providing a surrogate test procedure.

• The sensitivity of the gage to the changes in the surrounding medium seems to be a function of the ratio of the binder stiffness and the DART gage flexural rigidity. Initial testing indicates different DART gage sizes, construction, and/or materials will be required for testing asphalt binders over the entire stiffness regime.

• Of the various gages developed in the study, the outputs of the ADART #1C type gage offered the best possibility of evaluating asphalt binders over a range of stiffnesses of interest to unaged and aged asphalt binder testing. Specifically, this gage was sensitive to the asphalt medium when the storage modulus, G’, of the medium was in the range of 0.1 psi (0.69 kPa) to 4250 psi (29 MPa) and phase angle was between 30° to 75°. This somewhat limits the applicability of the DART to perform a full suite of binder testing that the DSR is capable of.

• Testing revealed that specimen size does not have a major impact on gage output at the frequencies of interest to the binder testing –1.59 Hz.

3.8.2 Recommendations for Standardized Gage Operation

Based on the results of the Phase I and II testing in air and in asphalt, the 1 inch ADART #1C gage with a total thickness of 20 mils (0.51 mm) (piezoceramic sheet thickness = 7.5 mils or
0.19 mm and stainless steel shim thickness = 5 mils or 0.13 mm) attached with a Micro Measurements EA-06-125AC-350 (or similar) strain gages was adopted as the standard for asphalt testing. The primary factors governing this decision are the ease of the construction of this gage from raw materials and its relatively large range of sensitivity. The gage can be driven at 120 V_{p-p} AC voltage at all temperatures and the DC excitation provided in the strain gage bridge can be as high as 15 VDC. This gage produced bending strains in the order of 0.0125 percent at the center of the duomorph gage when tested in air (which essentially represents the maximum strain encountered). The strain levels in the asphalt binder were lower than or equal to this value, depending on the temperature of testing. The asphalt binder is expected to be within the linear viscoelastic range at these strain levels when tested with this gage. It is recommended that testing in air should be immediately followed by testing in asphalt. Ideally, such testing should take place simultaneously. Strain gage data from the gage should be collected after the first 10 cycles of loading the gage to avoid overheating of the piezoelectric materials due to the applied DC bridge excitation.
The sensitivity of the DART gage to both the physical and mechanical properties of the asphalt medium has been clearly established during the laboratory prototype development. As demonstrated in Chapter 3, the raw DART strain signals can be used to establish a signature of an asphalt binder (modified or neat) in the laboratory. The DART can use this signature to “fingerprint” matching binders delivered to the field for acceptance, i.e., compare expected gage responses established in the laboratory for the specified asphalt over a range of temperatures or frequencies with field measured responses under the same conditions. While this is one of the applications, a more direct comparison of estimated mechanical properties of the asphalt with commonly tested dynamic mechanical properties of asphalt binders, e.g., shear modulus and phase angle is desirable. This chapter describes theoretical considerations of the DART gage behavior which could then form the basis for confirming the behavior of the gage observed in the laboratory and for computing the $G^*$ and $\delta$ of the asphalt using the DART gage outputs as a basis.

4.1 Analytical Modeling of the DART Gage

In their pioneering work, Briar, et al (1976) performed a quasi-static analysis and combined it with a numerical scheme to correlate the measured gage strains and shifts to the viscoelastic properties of the continuum. The theoretical considerations in this section text are taken entirely from the original work of Briar et al. (1976). They are included here to provide a context for the modeling work done under this dissertation.

Briar et al. (1976) made the following assumptions were made in performing the analysis; (a) classical thin plate theory fully describes the behavior of the DART gage, (b) the continuum is initially assumed to be linearly elastic and infinite in extent, (c) inertial effects are negligible for operational frequencies below 500 Hz, and, (d) the continuum stresses and deformations produced by the gage are significant to only within a cube of material having an edge length equal to twice the gage diameter.
Briar et al. (1976) describe three distinct steps in the analysis which lead up to establishing a relationship between the measured strains of the DART gage and the continuum properties. The first step is to predict the response of an infinite elastic body subject to arbitrarily distributed normal traction from an interior point. From the theory of elasticity, the axial or z-displacement of the elastic continuum due to a distributed pressure, P, acting in the z = 0 plane (Figure 46) is given by equation 11:

\[ w(R', 0) = w_0 = \frac{3R'}{4\pi E} \left[ I_1 + I_2 \right] \quad \text{Eq. (11)} \]

where

\[ E = \frac{(1 - \nu)E}{(1 - \nu)(1 - \frac{4}{3}\nu)} \quad \text{Eq. (12)} \]

\[ I_1 = \int_0^1 P(R' x_1^{0.5}) K(x_1) dx_1 \quad \text{Eq. (13)} \]

\[ I_2 = \int_{(R'/a)^2}^1 x_2^{-3/2} P(R' x_2^{-1/2}) K(x_2) dx_2 \quad \text{Eq. (14)} \]

where

- R' = radial distance from the center of the plate.
- E = Young's modulus of the continuum.
- P = pressure distribution on the gauge.

The function K = K(x) is a complete elliptic integral, which is defined as

\[ K(x) = \int_0^{\pi/2} (1 - x \sin^2 \phi)^{-1/2} d\phi \quad \text{Eq. (15)} \]

To evaluate the integrals I_1 and I_2, the pressure distribution, P, should be known. However, because this pressure is a function of the gage displacement, it is not known a priori. To offset this difficulty, a piecewise constant pressure distribution scheme is assumed. Under this scheme, the gage is divided into a central area and a series of N concentric rings. This leads to the expression of the total displacement as a summation of a finite set of constants, which greatly simplifies the solution.
The next step is to analyze the unconstrained DART gage to establish a companion set of relationships linking displacement and pressure. Within the context of classical plate theory, Briar et al. (1976) argue that applying a voltage to the gage on the bending strains and deflection are equivalent to applying a concentrated edge moment, $M_o$, around the gage’s periphery Figure 47.

\[
\begin{align*}
V \neq 0 & \quad = \quad V \neq 0 \\
& \quad + \quad V = 0
\end{align*}
\]

a) Unconstrained Gage \hspace{1cm} b) Constrained Gage \hspace{1cm} c) Mechanically Loaded Gage

Figure 47. Equivalence of loading conditions [from Briar et al. (1976)].

In the absence of any other load, the plate deflection, $w_m$, in the z direction, caused by the moment, $M_c$, acting at the edge $R = a$, from classical plate theory (Timoshenko and Woinowsky-Krieger 1987) is given by the expression:
where,

\[ R = \text{distance from the center of plate at which deflection is measured.} \]

\[ a = \text{plate radius.} \]

\[ v = \text{plate Poisson's ratio (previously defined).} \]

\[ D = \text{plate flexural rigidity (previously defined).} \]

In equation 15, when \( R \) equals \( a \), the gage displacement is arbitrarily taken as zero.

Finally, the consideration of equilibrium in the gage-continuum interaction analysis leads to the following matrix expression which is expressed entirely in terms of non-dimensional quantities:

\[
[W] \{q\} = \{I\} \quad \text{Eq. (16)}
\]

The column vector \( \{q\} \) represents the set of unknown non-dimensional pressures. \( \{I\} \) is a column vector with components specified as follows:

\[
I_i = \frac{i}{2(1+v)} \left(1 - \frac{i-1}{N}\right) \quad \text{for} \quad i = 1, 2, \ldots, N+1 \quad \text{Eq. (17)}
\]

\( N \) is the number of concentric rings into which the gage is divided. The elements of the \( (N+1) \times (N+1) \) square matrix \([W]\) are defined as:

\[
w_{ij} = \frac{3a_{ij}}{2\pi\hat{M}\sqrt{N}} + \frac{b_{ij}}{32N} + c_{ij} \quad \text{Eq. (18)}
\]

\( \hat{M} \) was the previously defined in equation (8). It provides a relationship between the asphalt binder stiffness and the gage stiffness and \( a_{ij}, b_{ij}, c_{ij} \) are matrix constants.
After the vector \( \{q\} \) is computed from equation 16, the quantities of interest in applications of the gage, such as the moment ratio \( \frac{M_c}{M_o} \), can be computed analytically from plate theory.

This moment ratio is a complex value comprising both the amplitude \( \frac{M_c}{M_o} \) and phase shift \( \theta_M \). It can be represented in the polar form as:

\[
\frac{M_c}{M_o} = \frac{M_c}{M_o} e^{-i\theta_M}
\]

Eq. (19)

\( M_c \) and \( M_o \) stand for plate central moment and applied edge moment, respectively. The magnitude of the moment ratio is related to the measured strains as follows:

\[
\left| \frac{M_c}{M_o} \right| = \left\| \frac{\varepsilon_c}{\varepsilon_a} \right\|
\]

Eq. (20)

\( \varepsilon_c \) and \( \varepsilon_a \) are strains at the center of the DART gage in the continuum and air respectively. This expression holds true for a DART gage whose deformation is symmetric about its neutral axis.

4.1.1 Extension to Viscoelasticity

Although the derivations illustrated to this point are premised on an elastic medium, they were extended by Briar et al. (1976) to accommodate viscoelastic continua through the application of the correspondence principle. This application requires the substitution of \( \hat{M} \) by \( \hat{M}^* \) and \( \nu \) by \( \nu^* \). The complex parameter \( \hat{M}^* \) may be written in rectangular form as:

\[
\hat{M}^* = \hat{M}' + i \hat{M}''
\]

Eq. (21)

where, \( i = \pm \sqrt{-1} \) and \( \hat{M}' \) and \( \hat{M}'' \) are real and imaginary parts of \( \hat{M}^* \), respectively. Also from equation 8 it follows that:
\[ \dot{M}' = \frac{\dot{E}'}{a^3/D} \quad \text{Eq. (22)} \]
\[ \dot{M}'' = \frac{\dot{E}''}{a^3/D} \quad \text{Eq. (23)} \]
\[ \tan \delta = \frac{\dot{E}''}{\dot{E}'} \quad \text{Eq. (24)} \]

where, \( \delta \) is the phase angle as defined previously.

Once \( E' \) and \( E'' \) are determined, the complex modulus can be determined employing the relationship:
\[ E^* = \sqrt{E'^2 + E''^2} \quad \text{Eq. (25)} \]

The shear modulus, \( G^* \), is then given by the expression
\[ G^* = \frac{E^*}{2(1 + \nu^*)} \quad \text{Eq. (26)} \]

Among all the parameters presented in equations 11 through 26, the only parameter that can be readily determined in the lab is the modified moment ratio (referred to in Chapter 3 as the ratio of DART gage strain in the asphalt at a given temperature and frequency and corresponding strain in air) from equations 19 and 20 and the DART gage signal shift (-\( \theta_M \)). With the help of these parameters, it is possible to backcalculate the real part of the non-dimensional stiffness parameter \( \dot{M}' \) and the phase angle \( \delta \) from a nomograph such as the one shown in Figure 48. This nomograph is numerically constructed from two families of curves sharing an independent axis. The first family of curves plots the magnitude of the modified moment ratio \( \frac{M'}{M_o} \) against \( \dot{M}' \) for various values of the loss tangent, \( \tan \delta \), and the second plots \( -\theta_M \), the phase shift angle induced in the response of the DART gage by the medium, against \( \dot{M}' \) again for various values of \( \tan \delta \). Using this nomograph, with values for both the modified moment ratio and the shift angle \(-\theta_M\), solutions for \( \dot{M}' \) and \( \tan \delta \) can be iteratively
determined. Employing equation 22 through equation 26 with these values, the desired viscoelastic properties of the continuum can be estimated.

![Typical DART data reduction nomograph (from Lavoie et al. 1996).](image)

**Figure 48.** Typical DART data reduction nomograph (from Lavoie et al. 1996).

### 4.1.2 Data Reduction

The following sequence of steps outline the data reduction scheme to be followed to obtain the continuum’s parameters using the nomograph:

1. **Step 1:** Obtain the strain at the center of the DART gage for a given voltage and frequency of testing in air and in the continuum—\( \varepsilon_a \) and \( \varepsilon_c \), respectively.
2. **Step 2:** Obtain the phase difference between the sinusoidal voltage input and the corresponding strain output in air as well as in the continuum—\( \theta_a \) and \( \theta_c \). The shift angle for the medium is then calculated as \( \theta_M = \theta_c - \theta_a \).
3. **Step 3:** For the given DART gage, establish the disk rigidity parameter D.
Step 4: Employing equation 20 determine the modified moment ratio $|M_c/M_0|$.

Step 5: Enter a nomograph such as the one shown in Figure 48 with the moment ratio from Step 4 and the shift angle from Step 2 and iteratively determine the values of $\dot{M}'$ and $\tan(\delta)$. Iterate until the differences between the respective parameters obtained from two successive steps fall within acceptable limits.

Step 6: Using $\dot{M}'$ and $\tan(\delta)$ obtained from Step 5 and employ equation 22 and equation 24 to compute $E'$ and $E''$, respectively.

Step 7: Finally, compute $E^*$ and $G^*$ from equations 25 and 26, respectively.

The data reduction procedure contains several steps that are time consuming. The two notable tasks being; (a) constructing a nomograph for the specific duomorph gage under consideration, and (b) performing iterations to obtain the desired moduli. However, the copyrighted DUONOMO and DUO_CALC computer programs developed by Grosz (Grosz, 1995), as part of the Office of Naval Research effort to adapt the DART for marine sediment testing (Lavoie 1994), help in greatly expediting the data reduction process. The DUONOMO program numerically constructs the nomograph for any given disk geometry and the DUO_CALC program uses this to compute $\dot{M}'$ and $\tan(\delta)$ iteratively. The inputs to the DUO_CALC program are the measured strains and shift angles in air and in asphalt. These programs are available in the public domain and can be used for construction of the nomographs for each DART gage.

4.1.3 Application of Analytical Approach to Reduce DART Data to Obtain Complex Moduli and Phase Angles

The solution scheme proposed by Briar et al. (1976) was used to reduce the data collected using the DART gages and reported in Chapter 3. The goal was to determine complex moduli and phase angles of the various binders tested.
4.1.3.1 Determination of Complex Shear Modulus

Testing of Tank/Original Binder

As discussed in Chapter 3, the DART gage was initially tested in an unaged AC-20 tank asphalt specimen. A cylindrical asphalt specimen having a height and diameter of 4 inches (101.6 mm) was prepared. Each DART gage was inserted into the specimen taking adequate care that it was centrally located in it. Gage responses in the asphalt medium were collected at the same frequencies and driving voltages at which the air tests were performed. Temperatures were varied over a wide range (0°C to 60°C or 32°F to 140°F).

Figure 49 compares the G* values for an unaged AC-20 binder obtained over a wide range of temperatures from DART #4A with those obtained from a research grade DSR at a test frequency of 1.59 Hz. There is a reasonable agreement in the trends between the DSR and the DART measured G* values. However, the DART seems to consistently overestimate the G* values over the range of temperatures at which the testing was performed.

![Figure 49](image_url)

Figure 49. Comparison of G* values for an unaged AC-20 binder using the data reduction scheme of Briar et al. (1976).
Testing of PAV Processed Binder

The PAV processed binder was tested using the DART gages as well as the DSR at various frequencies and temperatures. The asphalt sample was placed in a cylindrical container having a height and diameter of 2 inches (50.8 mm). Figure 50 compares the G* values of the PAV material obtained from DART # 2B to those obtained from the DSR at 22°C (72°F) and 30°C (86°F). Once again, although the data trends are reasonable, the bias between the DART gage and DSR responses is obvious from the figures with the DART gage underestimating the stiffnesses this time.

![Shear Modulus G* vs Frequency](image)

Figure 50. Comparison of G* values for a PAV aged AC-20 binder using the data reduction scheme of Briar et al. (1976).

4.1.3.2  Determination of the Phase Angle

Table 8 presents the phase angle comparisons for the original as well as the PAV asphalt, respectively. Although the data trends are reasonable, it can be concluded from the Table that some success was achieved in determining the phase angles. The agreement between the
phase angles for unaged binders is reasonable with a paired t-test indicating the estimates do not differ from each other at a significance level of 0.05 for the data shown.

Table 8. Phase Angle Comparisons for an AC-20 Binder.

<table>
<thead>
<tr>
<th>Temp, °C (°F)</th>
<th>DSR, degrees</th>
<th>DART, degrees</th>
<th>Temp, °C (°F)</th>
<th>DSR, degrees</th>
<th>DART, degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 (77)</td>
<td>49.4</td>
<td>54.4</td>
<td>22</td>
<td>33.4</td>
<td>42.2</td>
</tr>
<tr>
<td>30 (86)</td>
<td>64.0</td>
<td>57.1</td>
<td>25</td>
<td>34.1</td>
<td>44.9</td>
</tr>
<tr>
<td>35 (95)</td>
<td>72.7</td>
<td>60.9</td>
<td>30</td>
<td>35.0</td>
<td>48.7</td>
</tr>
</tbody>
</table>

Overall, the comparison between the DART and DSR measured complex shear moduli and phase angles were not satisfactory for the former parameter although the trends of the estimated parameters with respect to temperature, frequency of testing, and aging condition of the binder were reasonable. This calls into question the suitability of the current data reduction scheme to capture the sensitivity in an asphalt binder.

4.2 Finite Element Approach to Model Gage Behavior

A theoretical investigation of the DART gage was undertaken using the finite element approach to overcome some of the perceived limitations of the analytical approach of Briar et al. (1976) for asphalt binder characterization. There were multiple objectives for this investigation as described below:

- To develop an analytical model that appropriately describes the physical problem at hand.
- To confirm the gage design decisions made during the laboratory investigations. Recall that it was pointed out in Chapter 3 that DART gages with different flexural rigidities might be needed to for various stiffness regimes of the asphalt specimens. Flexural rigidities can be altered by varying either the mechanical
properties or the dimensions (diameter or thickness) of the gage. This trial and error process can be greatly facilitated by finite element simulations.

- To verify if the data reduction schemes from Briar et al. (1976) are applicable for asphalt binder evaluation. An associated objective through this investigation is to provide a framework for determining asphalt binder properties from the measured responses of the DART gage.
- To support future development of the DART gage by modeling other gage shapes and materials that can lead to lower production costs.

The main focus of the discussion will be on the development of a finite element model to simulate the responses of the ADART#1C gage in air and in asphalt. The main reason for the selection of this gage was that it produced consistent laboratory test results which can be used to validate the theoretical model. The inputs to the model include material properties of the gage obtained from the manufacturer, assumed properties of the asphalt binder, and the magnitude of the driving force. The primary outputs are the bending strain response at the center of the gage and the shift in the gage response with respect to the drive signal. The finite element responses was validated through laboratory measured ADART#1C responses thus establishing an analytical model to simulate the gage response.

4.2.1 Desired Capabilities of the Modeling Tool

Generally speaking, the DART gage’s behavior in air as well as in asphalt can be fully analyzed using a finite element program with following features:

- A library of finite elements with two- and three-dimensional elements capable of approximating the quadratic displacement field anticipated when the DART gage flexes back and forth in response to the applied electrical voltage. The elements should be capable of degrees of freedom related to both stress/strain analysis as well as piezoelectric analysis.
- A materials library that includes capabilities to model elastic, viscoelastic, and piezoelectric material behavior.
- Ability to perform static, steady state dynamic, and transient dynamic analysis.
- Ability to couple piezoelectric, dynamic, and viscoelastic analyses.

The general-purpose finite element program ABAQUS™ contains most of the desired features and was chosen to perform the analyses. ABAQUS offers a huge database of rigorously tested elements (including piezoelectric elements), materials, and procedure libraries that could be used in the analysis of the duomorph problem. Using ABAQUS, a finite element model of the DART gage could be constructed to varying degrees of complexity. Many types of coupled problems can also be solved. However, some limitations in the current version of the ABAQUS program were noted with regard to solving the duomorph problem. These include the inability of ABAQUS to model nonlinear piezoelectric materials and to perform piezoelectric analysis coupled with transient dynamic analysis. The latter limitation limits the ability of the program to perform the DART gage analysis in asphalt using time domain viscoelastic inputs. These shortcomings, however, did not hamper the overall analysis objectives of the study seriously since, for example, the DART gage is not expected to behave nonlinearly. Further, since the gage is expected to vibrate at a relatively low frequency (1.59 Hz), a steady state analysis is adequate to characterize the dynamic response and a transient dynamic analysis is not required.

4.2.2 Modeling the DART Gage Response

4.2.2.1 Key Analysis Assumption
Prior to developing a working finite element model of the DART gage, a simplifying assumption was made with regard to load definition. Strictly speaking, distributed or concentrated electrical charges applied to the electroded duomorph faces accurately define the loading of the DART gage. Although ABAQUS has the capability to apply this type of loading, the properties of the piezoceramic material, such as the piezoelectric stress or strain coefficient matrix and the dielectric coefficient matrix, that are required to support the analysis were difficult to obtain from the manufacturer for the specific materials used in the research. The constitutive equation governing the mechanical behavior of the gage requires either the piezoelectric stress coefficient or strain coefficient matrix as input, whereas, the
equation governing the electrical behavior requires a dielectric property matrix as input. A
definition of the piezoelectric behavior in the most general way (anisotropic behavior)
requires 18 independent constants for the piezoelectric stress or strain coefficient matrix and
6 constants for the dielectric matrix. This data was very difficult to obtain.

In order to overcome this problem, the approach of Briar et al. (1976) was consulted. In their
approach, Briar et al. (1976) showed that, within the context of classical plate theory, the
effect of applying a voltage to the gage for the bending strain and deflection is same as
applying a concentrated moment around the gage’s periphery. Recognizing that the DART
gage in bending is similar to a thin plate in bending, this equivalence can be taken advantage
of without much loss of generality. The equivalence between the electrical and mechanical
loads is shown in Figure 47 and transforms the problem from a piezoelectric domain to a
mechanical domain. Several other advantages brought about by this equivalence included
reduced model complexity due to simplification of materials inputs and reduced
computational time.

4.2.2.2 Duomorph Response in Air
As a first step in the analysis, the response of the DART gage in air was modeled. The
various considerations in performing this analysis are explained below. In the second step,
the response of the gage after it was embedded into the asphalt medium was analyzed.
Obviously, decisions taken regarding the element type, mesh refinement, and loading in the
first step carry over to the second step.

Model Geometry

The ADART#1C is a circular gage 1-in in diameter and 0.02-in or 0.508-mm thick (7.5 mils
or 0.19 mm thick piezoceramic layers and 5 mils or 0.13 mm thick steel shim). Since the
DART gage is essentially a thin solid of revolution, axisymmetric analysis was assumed to
be appropriate. The symmetry afforded by the model was taken advantage of and only one-
half of the model was considered for meshing.
Element Selection and Meshing

Since the DART gage is only operated in flexure mode, finite element types that can accurately represent this mode of deformation were chosen from the ABAQUS element library along with other element to provide a basis for comparison. Three different axisymmetric element types were utilized to solve the problem including 4-noded bilinear elements (CAX4), 4-noded bilinear, incompatible mode elements (CAX4I), and 8-noded biquadratic elements (CAX8). Incompatible mode elements are first-order elements that are enhanced by incompatible modes to improve their bending behavior. The active degrees of freedom in all these element types are the radial and axial displacements, $u_r$ and $u_z$, respectively.

Three different meshes were configured with each element type to form a matrix of 9 finite element meshes. The coarsest mesh comprised of 45 elements and the finest mesh had 1140 elements. Since the maximum strain gradients from the applied edge moments are anticipated to occur closer to the line of symmetry, care was taken in the mesh development to bias the nodes closer to this location in each of the 9 meshes.

Material Definition

The difficulty in obtaining piezoelectric material inputs has already been discussed in a preceding section. Since the problem has been converted to the mechanical domain, the only inputs required for the analysis are the Young’s modulus and Poisson’s ratio of the steel shim and the piezoceramic layers. For the purposes of this study, the piezoceramic and steel layers were modeled as isotropic, linear elastic materials. The material properties used in the analysis are given in Table 9. Note that, for the piezoceramic layer, the manufacturer supplied Young’s modulus values in the 31 direction, $E_{31}$, was used. $E_{31}$ is more appropriate because it represents the material property when the applied electric field is along the polarization axis and the resulting deformation is perpendicular to it as is the case when the ADART#1C gage is in operation.
Table 9. ADART#1C gage material properties.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Young’s Modulus</th>
<th>Poisson’s Ratio</th>
<th>Mass Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSI-5A-S2</td>
<td>$E = 8.3 \times 10^6$ psi or $5.7 \times 10^{10}$ Pa</td>
<td>0.30</td>
<td>485 lb/ft$^2$ or 7750 kg/m$^3$</td>
</tr>
<tr>
<td>Piezoceramic material</td>
<td>$E = 30 \times 10^6$ psi or $2.1 \times 10^{11}$ Pa</td>
<td>0.25</td>
<td>470 lb/ft$^2$ or 7500 kg/m$^3$</td>
</tr>
</tbody>
</table>

Boundary Conditions

Assigning boundary conditions to the DART problem proved to be a difficult task. In reality, the DART gage is held in position in space by the electrical leads attached to it and the frame that houses it (see Figure 23). However, it is not practical to translate this into a degree-of-freedom (d.o.f) based restraint required to perform the finite element analysis. In order to overcome this difficulty, the analysis of the gage’s bending behavior by Briar et al. is once again consulted. In their idealization, Briar et al. (1976) made a valid assumption that the neutral axis remains fixed in bending, as shown in Figure 47, as the gage flexes back and forth under the applied AC voltage. This can be assured, in the finite element analysis, by preventing the nodes that lie on circumference of the duomorph, at the level of the neutral axis, from translating in a direction perpendicular to the plane of the neutral axis.

The boundary conditions applied to the model define symmetry at the left edge (see Figure 51 [left]) (radial displacement, $u_r = 0$) and restrict rigid body motion at point B (axial displacement, $u_z = 0$).

![Figure 51. Applying an edge moment to the axisymmetric finite element mesh.](image)
Loading

As discussed previously, edge moments are applied to the finite element model representing the gage in lieu of the electrical loads. However, the degrees of freedom needed to apply rotations or moments at nodes are not active in axisymmetric analysis. Therefore, prior to the application of the load, the edge moment had to be converted to equivalent non-uniform element edge loads as shown in Figure 51 (right). The edge loads were varied sinusoidally at 1.59 Hz to simulate the laboratory application of the AC voltage of similar frequency.

Another challenge in the analysis was to determine the magnitude of the force $p_0$ that produces an edge moment corresponding to an AC voltage of 120 V$_{p-p}$ used to drive the duomorph in the laboratory. This was determined iteratively by continually matching laboratory measured bending strain at point A, in Figure 51 (left), with those from the finite element analysis produced by a succession of arbitrarily assumed moments. The magnitude of force $p_0$ that produced a strain closely matching the laboratory-measured value was assumed as the mechanical equivalent of the electrical load. This was held constant for all the finite element meshes. The nonlinearly distributed edge traction shown in Figure 51 (right) is then converted to nodal traction vector by the finite element program for each of the finite element meshes under consideration.

Results and Discussion

A steady state dynamic analysis was performed using the ABAQUS *STEADY STATE DYNAMICS procedure. The frequency of loading was 1.59 Hz. The two parameters of interest to the finite element calculations, the peak bending strain at the center of the DART gage ($E_{11}$) and the shift in the gage response with respect to the drive signal when the peak strain is achieved, were computed. As expected, the phase shift was zero degrees in all cases. The bending strains for the each of the 9 finite element meshes are shown in Figure 52.
Figure 52. Mesh convergence study for the duomorph gage.

Since the load on the finite element meshes has already been pre-adjusted to produce the laboratory measured strains, matching the calculated strains with measured strains will be a trivial exercise. However, the results shown in Figure 52 were used to infer the suitability of the element types considered in performing the duomorph strains. It can be inferred from the figure that the finite element mesh with CAX8 elements was able to converge to the exact solution even with as few as 45 elements, whereas, the mesh with CAX4 elements converges to the exact solution only at 1440 elements. The mesh with CAX4I elements also converges with a small number of elements but shows a “softer” response compared to the mesh with the CAX8 elements.

Model Validation

Based on this analysis it can be concluded that the CAX8 elements are appropriate to model the DART gage bending accurately. Further proof of the ability of these elements is obtained by comparing the non-dimensionalized deflection profile of the DART gage obtained from the finite element analysis with profiles determined theoretically using plate theory. This comparison is shown in Figure 53. Laboratory measured ADART#1C strains at the gage center was used to non-dimensionalize the calculated strains. Briar and Bills (1972)
performed interference holographic analysis and also noted a close correlation between the theoretical and experimental deflections.

Another type of element that was considered for modeling the duomorph behavior was the laminated axisymmetric shell element SAX1 (2-node thin or thick linear shell using three degrees of freedom per node). Shell elements were deemed appropriate considering the thinness of the plate and the fact that the plate, when subject to the moments described, is expected to simultaneously display bending as well as membrane stresses—a characteristic of shell behavior. Results from the usage of these elements were close to those from the CAX8 idealization of the ADART#1C gage. However, some potential complexities such as the use of contact elements and incompatible element types were perceived when the shell-element based gage model in air is extended to incorporate the asphalt medium. Therefore, the CAX8 elements were pursued in the next stage of analysis.

4.2.3 Extending the Gage Finite Element Model to Understand Gage-Asphalt Continuum Interaction

In this section, the DART gage model when operating freely in air was extended to study the asphalt embedded gage problem. The response of the gage after it was embedded into the asphalt medium was analyzed. The various considerations in modeling this response are
presented below. Obviously, decisions taken regarding the element type, mesh refinement, and loading for the DART gage and discussed above were carried over to this stage of the analytical framework development.

4.2.3.1 Model Geometry
The cylindrical asphalt specimen with a circular gage embedded in it lends itself well to axisymmetric analysis. The dimensions of the tank and PAV specimen have already been discussed in Chapter 3. Figure 54 shows the arrangement of the DART gage within a tank asphalt specimen. The symmetry afforded by the model was once again taken advantage of and only one-half of the geometry was considered for meshing.

![Figure 54. Geometry of asphalt specimen with embedded duomorph.](image)

4.2.3.2 Element Selection and Meshing
Since CAX8 type elements were found to be adequate to model the gage behavior, they were chosen to mesh the asphalt medium as well to ensure element compatibility. The interface between the gage and the asphalt as meshed continuously, i.e., contact elements were not used. This is a valid approach since the gage and the asphalt binder surrounding it are not expected to debond over the range of temperatures and frequencies considered in this
analysis. Recall that the gage is embedded in the asphalt when it is hot ensuring a bond between the two materials. The advantage of using the CAX8 element type for the gage analysis over the shell elements is also obvious at this point. The use of the SAX1 type shell elements would have entailed the computationally intensive contact analysis due to the incompatibility in the element types.

The finite element mesh, loading, and boundary conditions of the DART gage from the prior analysis were retained. A nonuniform mesh was generated over the asphalt specimen using CAX8 elements taking care to bias the nodes in both directions to produce a finer mesh around the flexing DART gage since this is the region of interest. Three different mesh sizes comprising of 2150, 3780, and 5580 elements respectively were meshed to check for convergence.

4.2.3.3 Material Definition

The asphalt embedded gage problem can be modeled using the frequency-domain viscoelastic material model in ABAQUS since the excitation of the asphalt due to the DART system falls under the realm of steady-state small vibration analysis. The frequency-domain viscoelastic material model in ABAQUS is isotropic and linear which is adequate to describe asphalt binder behavior. Therefore, the asphalt binder was modeled as a linear viscoelastic material using the *VISCOELASTIC option in ABAQUS. The viscoelastic material inputs to the model can be input in a tabular form as pairs of modulus versus frequency. Both the real and imaginary part of the complex shear modulus, \( G' \) and \( G'' \), must be entered in the normalized form. The normalization can be achieved as indicated in equations 27 and 28 below:

\[
\begin{align*}
\omega R(g^*) &= \frac{G''}{G_\infty} & \text{Eq. 27} \\
\omega I(g^*) &= 1 - \frac{G'}{G_\infty} & \text{Eq. 28}
\end{align*}
\]

\( G_\infty \) forms an additional input to the material model and represents the long-term elasticity of the material. This must be defined in ABAQUS using the option *ELASTIC. In theory, this value corresponds to the shear modulus of the material when the loading frequency is
infinity. ABAQUS reads the tabular frequency response input data and converts it into a power law equation for convenience of computation. Note that the definition of the components of the bulk modulus, required to complete the material characterization, is not required in this analysis since the material is near incompressible.

The modulus frequency pairs for the asphalt binders under consideration were determined by performing frequency and temperature sweep testing using a research grade DSR. Data were obtained over a frequency range of 0.1 Hz to 100 Hz for each of the asphalts and over a temperature range of 5°C (41°F) to 60°C (140°F). Figure 55 presents an example of the complex shear modulus response at various frequencies and test temperatures determined using the DSR for the AC-10 grade asphalt binder. Similar data were collected for the storage modulus, \( G' \), loss modulus, \( G'' \), and the loss tangent, \( \tan \delta \) for each of the three asphalt binders under consideration.

![Graph of G* vs. Frequency](image)

1 kPa = 0.145 psi

Figure 55. Example plot of DSR output—\( G^* \) vs. frequency.

The long-term shear modulus for each of the curves in Figure 55 was estimated by extrapolation as value at a frequency of 10,000 Hz. The logic behind choosing this frequency was that it is approximately four decades away from the frequency of interest—1.59 Hz. Further, the \( G^* \) vs. frequency curves tend to flatten out and converge at this high
frequency. The Poisson’s ratio of the asphalt binder was assumed as 0.49. The material properties of the DART gage have already been discussed in section 4.2.2.2.

4.2.3.4 Boundary Conditions

Since symmetry afforded by the model was taken advantage of for computational efficiency, nodes lying on the axis of symmetry will obviously have symmetry conditions applied to them, i.e., $u_r = 0$. Recall that in the CAX8 type finite elements only translational d.o.f’s are active. The cylindrical asphalt specimen with the embedded gage shown in Figure 54 is placed in a glass container (Figure 23). Consequently, the restrictions imposed by the container on the asphalt specimen translate into displacement-based boundary conditions for the finite element model.

Since the nodes lying on the bottom edge of the specimen in Figure 54 are prevented from translating in the $z$-direction, a displacement boundary condition of $u_z = 0$ is appropriate for these nodes. For nodes lying on the right edge of the specimen, since the radial displacements are restricted by the container, a boundary condition of $u_r = 0$ is applied for these nodes. Theoretically, these nodes are free to translate in the $z$-direction along the walls of the container. Finally, since the top surface of the specimen is unrestricted no displacement boundary conditions are needed on this face.

4.2.3.5 Loading

The only loading in the model is on the duomorph gage which has already been discussed in section 4.2.2.2. The magnitude of the edge moment determined for the duomorph analysis in air was held constant in the analysis. This provides direct comparisons of the duomorph response in air and in asphalt.
4.2.3.6  Mesh Convergence

The three meshes configured with varying degrees of mesh refinement were analyzed for mesh convergence using the boundary conditions and loading defined so far. The material definitions used in the analysis were that for the AC-10 tank binder tested at 16°C (61°F). The parameters under investigation for the mesh convergence study were the bending strain at the center of the DART gage (point A in Figure 54). Based on this analysis, the following conclusions were arrived at:

- The bending strain solution converged quickly to a constant value. In fact, there was no appreciable difference in the strain value between the three meshes.
- The contour plots of the strain field indicate that, in most instances, at a distance of about 2r to 3r on either side of the DART gage, in the direction of motion (z-direction in Figure 54), the strain magnitudes dissipated to negligible levels compared to the strain at point A.

Based on these findings a finite element mesh with 3780 elements was conservatively adopted for the analysis since some of the meshing characteristics of this mesh obeyed commonly followed rules of thumb while generating finite element meshes. For example, in this mesh care was taken to ensure that while transitioning from one element size to the next, the ratio of the adjacent element lengths was kept between 1.5 to 2.0 to ensure smooth displacement and strain gradients. Further, the largest finite element aspect ratio anywhere in the mesh was in the vicinity of 5.0. Figure 56 presents the finite element mesh utilized for all further analyses.

4.2.3.7  Model Validation

Several finite element runs were performed for each of the three asphalt binders under consideration using the finalized finite element mesh. Each run corresponded to a particular temperature for which the frequency-modulus curves were determined from the DSR for a given asphalt binder. The finite element output from each analysis was the maximum bending strain at the center of the DART gage and the associated signal shift. These maximum gage bending strain outputs in asphalt were divided by the previously calculated
maximum gage strain output in air to obtain a strain ratio. The strain ratio from each finite
element run was then compared with those determined experimentally at the same
temperature and under the same loading conditions for each of the asphalt binders. The
comparisons between the finite element and laboratory strain ratios for AC-10, AC-40, and
AC-20 PAV binders are shown in Figure 57 through Figure 59, respectively. Corresponding
comparison plots for the same asphalt binders for signal shifts are presented in Figure 60
through Figure 62.

Figure 56. Finite element mesh of the showing the duomorph gage embedded in asphalt.
Figure 57. Comparison between finite element and experimentally determined strain ratios for AC-10 tank asphalt.

Figure 58. Comparison between finite element and experimentally determined strain ratios for AC-40 tank asphalt.
Figure 59. Comparison between finite element and experimentally determined strain ratios for AC-20 PAV aged asphalt.

Figure 60. Comparison between finite element and experimentally determined signal shifts for AC-10 tank asphalt.
Figure 61. Comparison between finite element and experimentally determined signal shifts for AC-40 tank asphalt.

Figure 62. Comparison between finite element and experimentally determined signal shifts for AC-20 PAV aged asphalt.
The following observations regarding the finite element model of the duomorph were made based on the results presented:

- The observed trends in the outputs of the finite element model agree extremely well with the experimental data. This observation verifies the finite element model of the DART gage.
- The finite element outputs are validated by the experimental data. In all cases, the correlation coefficient between the observed and predicted value is in excess of 0.90 with a majority of the comparisons exceeding an R² of 0.95.
- The limitation of the ADART#1C gage to provide reasonable stiffness data in the laboratory beyond 40°C (104°F) in AC-10 asphalt and 45°C (113°F) in AC-40 tank asphalts is confirmed by the analysis. However, the range of temperature over which the ADART#1C gage can produce valid data increases with the increase in stiffness of the binder as evidenced by the data from stiffer AC-20 PAV aged asphalt.

4.2.3.8 Additional Analysis of DART Gage Response in Asphalt

As was noted in the discussion at the end of section 3.5, using a gage with a lower flexural rigidity can increase the sensitivity of the DART gage at the high temperatures or low stiffnesses. This is demonstrated in the analysis presented in Figure 63 where the material properties of a “soft” asphalt were held constant and the gage flexural rigidity was varied until satisfactory strain ratios were obtained. The disk flexural rigidity required to obtain a strain ratio of 0.4 in a “soft” asphalt—a ratio representing the “sweet spot” for DART’s effectiveness range—is within the realm of practical engineering piezoelectric materials.
1 psi = 6.89 kPa

Figure 63. Analysis of the influence of duomorph gage flexural rigidity on the strain ratio.
CHAPTER 5. PROPOSED DART GAGE DATA REDUCTION PROCEDURE

The theoretical basis for understanding the DART gage behavior prior to the development of the finite element model used in this research was the analytical procedures developed by Briar et al. (1976). As described in Chapter 4, this model relied on a combination of thin plate theory for the gage operation, a continuum mechanics approach for bulk response of the asphalt medium, and a boundary condition approach for modeling the gage-asphalt interaction. It utilized the linear elastic-viscoelastic correspondence principle and numerical techniques to determine the gage responses for a given loading condition. As is common with such analyses a number of simplifying assumptions were made regarding the gage, the continuum and their interaction. A nomographical solution was developed based on the analytical framework developed which was later computerized by Grosz et al (1995). As noted in Chapter 4, the underlying assumptions in the work of Briar et al. (1976) are suspected to limit the applicability of the proposed nomographical solution to reducing properties of asphalt binders. This chapter describes the development of a new data reduction scheme using the validated finite element models of the DART gage. The data reduction scheme is expected to provide a better basis for reducing the DART gage response data to estimate the binder’s complex shear modulus, G*, and phase angle, \( \delta \). The data reduction scheme is based on the same nomographical approach used by Briar et al. (1976) but with more specific relationships between the DART gage’s laboratory measured strain ratio and phase shift with the dimensional stiffness term, \( M' \), and phase angle, \( \delta \), for asphalt binders.

5.1 Parametric Study

Using the finalized axisymmetric finite element meshes of the ADART #1C gage operating in air (180 CAX8 element mesh) and in asphalt (3780 CAX8 element mesh) from Chapter 4, a parametric study was conducted to develop a database of gage responses (strain at the center of the gage and the corresponding shift angle) for a range of assumed asphalt linear
viscoelastic material inputs. The ADART #1C gage was chosen because it was recommended in this dissertation as the standard DART gage for testing asphalt binders.

5.1.1 Asphalt Material Properties

Since the embedded DART gage problem is solved in the frequency-domain using assumptions of isotropy and linear viscoelasticity, complex modulus data need to be supplied to characterize the asphalt binder as a function of frequency. Specifically, both the storage and loss moduli, \( G' \) and \( G'' \) respectively, must be entered in the normalized form (normalized with respect to long-term elasticity of the material \( G_\infty \)) at the frequency values of interest to the analysis along with \( G_\infty \). The range of asphalt properties selected to conduct the finite element modeling parametric study establishes the range over which the solution database will be accurate. Recall from Chapter 3 that the ADART #1C gage was estimated to be sensitive to the asphalt medium when the storage modulus, \( G' \), of the medium was in the range of 0.1 psi (0.69 kPa) to 4250 psi (29 MPa) and phase angle was between 30° to 75°. Based on a review of published literature (Witczak et al. [1998], Bonaquist et al. [1998], Zeng et al. [2001]) and Malpass [2003]), the DART gage operating limits therefore cover a wide range of viscoelastic properties of neat, modified, and recycled asphalt pavement (RAP) binders.

The following steps were taken to set up the asphalt binder materials inputs for the parametric study.

1. The isothermal \( G^* \) frequency sweep data from the four reference binders studied in this research—AC-10, AC-20, AC-40, AC-20(PAV aged)—tested at 8 temperatures ranging from 40°C (104°F ) to 135°C (275°F) were used to develop the asphalt material input datasets. The \( G^* \) versus frequency curves at different temperatures for each binder were fit to a Prony series and the parameters of the resulting fit were extrapolated to define the long-term elasticity value of the binder, \( G_\infty \). The long-term elasticity value was determined at a frequency of 10,000 Hz as described in Chapter 4.
2. A set of $\delta$ values at 5-degree increments were subsequently assumed to cover the range over which the DART gage is expected to be effective, i.e., $30^\circ$ to $75^\circ$. For each selected $\delta$, the storage and loss moduli, $G'$ and $G''$ were computed at each frequency from the Prony fit curves obtained in Step 1.

Figure 64 and Figure 65 respectively illustrate the $G'$ and $G''$ versus frequency curves developed for an AC-10 binder by taking the $G^*$ versus frequency curve at a single temperature and adjusting as noted in steps 1 and 2 described above. The combination of binder type, test temperatures, and tan($\delta$) values resulted in a total of 320 $G'$ and $G''$ versus frequency curves which formed the input database for the asphalt material.

5.1.2 DART Gage Properties

The properties assumed for the ADART#1C gage for the simulations were as noted below:

- Gage diameter: 1 inch (25.4 mm) diameter gage.
- PZT layer thickness: 7.5 mil (0.19 mm).
- Center shim: Stainless steel.
- Shim thickness: 5 mil (0.13 mm).
- PZT layer elastic modulus: $8.27 \times 10^6$ psi (57 GPa).
- PZT layer Poisson’s ratio: 0.3.
- Stainless steel elastic modulus: $30 \times 10^6$ psi (207 GPa).
- Stainless steel Poisson’s ratio: 0.3.

5.1.3 Boundary Conditions

The boundary condition assumptions for the finite element mesh of the gage when operating freely in air and when embedded in asphalt were kept similar to the analysis performed in Chapter 4.
1 psi = 6.89 kPa

Figure 64. $G'$ versus frequency plots for an AC-10 binder tested at 7°C (45°F).

Figure 65. $G''$ versus frequency plots for an AC-10 binder tested at 7°C (45°F).
5.1.4 Loading

As discussed in Chapter 4, non-uniform element edge loads were applied to the ADART#1C gage finite element mesh (see Figure 51[b]) to simulate the application of an electrical pulse to the electroded surfaces. Since only the ratio of strain in asphalt to that in air is of interest to the solution scheme, the magnitude of load is of no consequence. However, for continuity of discussion, the same loading levels used in Chapter 4 were persisted with in this parametric study. As discussed in Chapter 4, the magnitude of the force $p_0$ that produces an edge moment corresponding to an AC voltage of 120 Vp-p was determined by matching lab measured bending strain at point A in Figure 51 for the ADART#1C gage operating freely in air. Once this load level was determined, it was maintained to compute the strain at the center of the ADART#1C gage when operating in the various simulated asphalt binders. This was done to facilitate a direct comparison of the outputs of gage in air and in asphalt. As discussed in Chapter 4, the edge loads were varied sinusoidally at 1.59 Hz to simulate the laboratory application of the AC voltage of similar frequency. This frequency was chosen for the simulations since it is the recommended standard frequency for testing DART gages in asphalt binders and is also the standard DSR test frequency in the AASHTO M320 specification.

5.1.5 Development of the Response Database

A total of 320 finite element runs were executed for the asphalt embedded gage problem for the various sets of assumed asphalt properties. For each run, the following outputs were recorded--bending strain at the gage center ($\varepsilon_{ac}$) and phase shift lag at the gage center ($\theta_{ac}$).

One additional finite element run was executed for the gage operating freely in air to establish the calibration point to compare the embedded gage responses ($\varepsilon_{ac}$ and $\theta_{ac}$) with. The bending strain ($\varepsilon_{air}$) and phase shift at the gage center when operating freely in air ($\theta_{air}$) were recorded. Note that as expected, $\theta_{air}$ was zero indicating no shift between the drive signal and gage output.
Subsequently, the ratio of strain of the gage in asphalt and in air ($\varepsilon_{ac}/\varepsilon_{air}$) for each of the 320 finite element runs and the corresponding differences in phase shifts ($\theta_{ac}-\theta_{air} = \theta_{ac}-0 = \theta_{ac}$) were computed and stored in a database along with the raw responses.

5.2 Results and Discussion

Following the data reduction scheme developed by Briar et al. (1976), a nomograph was developed using the results of the various finite element runs to help estimate the continuum properties $G^*$ and $\delta$ from the gage strain ratio ($\varepsilon_{ac}/\varepsilon_{air}$) and phase shift ($\theta_{ac}$).

Figure 66 presents the ADART#1C data reduction nomograph based on the results of the finite element simulations. The strain ratio term is chosen as one of the dependent variables as opposed to the moment ratio term used by Briar et al. (1976) because strains are directly computed in the FE-based approach used. Equation 29 presents the analytical expression relating the strain ratio and $M'$ for each tan($\delta$) value shown in Figure 67. The goodness-of-fit statistics and plot for this expression are presented in Figure 67. Similarly, equation 30 presents the expression relating phase shift and $M'$ for each tan($\delta$) value shown in Figure 66. The corresponding goodness-of-fit statistics and plot for this expression are presented in Figure 68.

\[
Strain\ Ratio\ (\varepsilon_{ac}/\varepsilon_{air}) = A0 e^{-A1 M'} + A2 e^{-A3 M'} + A4 e^{-A5 M'} \quad Eq. \ (29)
\]

where,

<table>
<thead>
<tr>
<th>Tan($\delta$)</th>
<th>A0</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
<th>A5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.71539</td>
<td>49.99999</td>
<td>0.989359</td>
<td>0.206643</td>
<td>0.095278</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.70576</td>
<td>50.0001</td>
<td>0.949444</td>
<td>0.236279</td>
<td>0.14594</td>
<td>0.001804</td>
</tr>
<tr>
<td>1.5</td>
<td>0.216281</td>
<td>0.00922</td>
<td>0.672621</td>
<td>26.21183</td>
<td>0.893531</td>
<td>0.291165</td>
</tr>
<tr>
<td>2</td>
<td>0.69493</td>
<td>50.00001</td>
<td>0.24742</td>
<td>0.012512</td>
<td>0.867803</td>
<td>0.33242</td>
</tr>
<tr>
<td>2.5</td>
<td>0.68684</td>
<td>50.00001</td>
<td>0.862958</td>
<td>0.365943</td>
<td>0.26304</td>
<td>0.013816</td>
</tr>
</tbody>
</table>
Figure 66. The ADART#1C gage data reduction nomograph.

Figure 67. Comparison of strain ratios from the finite element model runs and the regression equations that fit the data from the finite element model runs.
Phase Shift \( (\theta_{ac}-\theta_{air}) = \frac{A0}{A1 + A2 \cdot M'^{A3}} \) \hspace{1cm} \text{Eq. (30)}

where,

<table>
<thead>
<tr>
<th>( \tan(\delta) )</th>
<th>( A0 )</th>
<th>( A1 )</th>
<th>( A2 )</th>
<th>( A3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>282.62</td>
<td>1</td>
<td>163.48</td>
<td>1.5022</td>
</tr>
<tr>
<td>1</td>
<td>252.40</td>
<td>1</td>
<td>34.50</td>
<td>1.2100</td>
</tr>
<tr>
<td>1.5</td>
<td>266.45</td>
<td>1</td>
<td>17.98</td>
<td>1.0639</td>
</tr>
<tr>
<td>2</td>
<td>277.42</td>
<td>1</td>
<td>12.55</td>
<td>0.9990</td>
</tr>
<tr>
<td>2.5</td>
<td>291.50</td>
<td>1</td>
<td>10.02</td>
<td>0.9493</td>
</tr>
</tbody>
</table>

Model Statistics:
\[ y = 0.9996x \]
\[ R^2 = 0.999 \]
\[ \text{RMSE} = 2.11 \]

Figure 68. Comparison of phase shifts from the finite element model runs and the regression equations that fit the data from the finite element model runs.

Comparing the FE-based nomograph in Figure 66 with that derived by Briar et al. (1976) in Figure 48, the following key observations can be made:

- The overall trends of the finite element (FE) based strain ratio to \( M' \) and phase shift \( (\theta_{ac}-\theta_{air}) \) to \( M' \) relationships are similar those reported by Briar et al. (1976).
• As noted by Briar et al. (1976), the strain ratio has a weak correlation with $\delta$ of the asphalt medium into which the DART gage is embedded.

• For smaller values of $M'$, the slope of the strain ratio versus $M'$ plot for any given $\tan(\delta)$ is steeper in the FE-based nomograph than that estimated by Briar et al (1976) for a gage with similar properties as the ADART#1C gage used in the finite element simulations. Also, the estimated strain ratios are smaller in this range of $M'$ values. Furthermore, for the FE-based nomograph, the slope of the strain ratio to $M'$ curve flattens out faster than the nomograph from the analytical solution of Briar et al. (1976).

Figure 69 provides a closer comparison between the FE-based solution scheme and that of Briar et al. (1976) for two $\tan(\delta)$ values. It is clear from the comparison that, for a $\tan(\delta)$ of 0.5, the solution scheme suggested by Briar et al. (1976) overestimates the strain ratio for $M'$ values less than approximately 30 and slightly underestimates it when $M'$ is greater than that 30. Similarly, for a $\tan(\delta)$ of 1.0, the solution scheme of Briar et al. (1976) overestimates the strain ratio for $M'$ values less than approximately 22.5 and underestimates it when $M'$ is greater than 22.5. These observations conversely imply that, when using the original solution scheme of Briar et al. (1976), the $M'$ estimates are likely to be higher or lower depending on the strain ratio and $\tan(\delta)$ values. For example, the overestimation of the unaged AC-20 DSR $G^*$ by the DART #4A in Figure 49 can now be explained with the help of the strain ratio versus $M'$ for this gage presented in Figure 36. The useful strain ratios for this gage are typically in the range of 0.2 or greater. For these strain ratios, the solution scheme of Briar et al. (1976) overestimates $M'$ and hence $G^*$ for both the $\tan(\delta)$ values shown in Figure 69. Although not shown in this figure, this statement is also true for all other $\tan(\delta)$ values. Note from Figure 49 that the $G^*$ values estimated from the DART using the Briar et al. (1976) solution scheme were overestimated when compared to corresponding DSR values.

Likewise, the underestimation of the PAV-aged AC-20 $G^*$ by the DART when compared to the DSR estimates (see Figure 50) can also be explained. The $M'$ of the DART #1C gage when operating in a PAV-aged AC-20 binder is above 30 and the strain ratio is typically below 0.1 (see Figure 37). For strain ratios below 0.1, Figure 69 shows that the solution
scheme of Briar et al. (1976) overestimates the M’ and hence G* for estimated M’ values of greater than 22.5 when tan(δ) is 0.5 and 30 when tan(δ) is 1.0—the typical M’ range for the ADART#1C gage operating in a PAV-aged binder at intermediate temperatures.

Figure 69. Comparison of FE based and Briar et al. (1976) analytical solutions for predicting strain ratio as a function of M’ and tan(δ).

Figure 70 presents a comparison of FE-based and Briar et al.’s (1976) solutions for predicting phase shift as a function of M’ and tan(δ). As can be noted from the figure, the phase shift is significantly underpredicted by the Briar et al. (1976) solution scheme. It is difficult to easily explain the impacts of this underprediction on the estimation of the phase angle δ using the DART outputs due to the strong dependence of tan(δ) on the phase shift and M’. Suffice to say that this underprediction will have an impact on both estimated M’ and δ from the DART measurement system.
Figure 70. Comparison of FE based and Briar et al. (1976) analytical solutions for predicting phase shift as a function of $M'$ and $\tan(\phi)$.

5.3 Data Reduction Application

The results of the FE-based parametric analysis of the ADART#1C gage establish a framework to reduce the DART gage laboratory responses to estimate the asphalt binder properties of interest to this research. Laboratory measured strain ratio and phase shift data from the ADART#1C gage can be used in conjunction with Figure 66 and equations 29 and 30 to estimate $G^*$ and $\delta$ using the following sequence of steps:

1. Enter the nomograph in Figure 66 with known values of strain ratio and phase shift.
2. Estimate an initial $M'$ for an assumed value of $\tan(\delta)$, say 1.0, based on equation 29.
3. For the $M'$ estimated from Step 2 and the known phase shift, estimate a new $\tan(\delta)$. This step may require interpolation between the various $M'$ versus phase shift curves (equation 30) to estimate the $\tan(\delta)$ value.

4. With the new $\tan(\delta)$ value from Step 3 and the known strain ratio (from Step 1), enter the nomograph in Figure 66 to develop an revised estimate of $M'$ (as noted in Step 2).

5. Iterate steps 2 through 4 as many times as necessary to obtain successive estimates of $M'$ and $\tan(\delta)$ that are within preset tolerance limits, e.g., 2 percent.


Using the solution scheme presented, the data reduction approach was validated for different combinations of asphalt binder $G^*$ and $\delta$ shown in Table 10. The $G^*$ and $\delta$ shown in the table were estimated using a research grade DSR at a test frequency of 1.59 Hz. Figure 71 presents a comparison of the DSR measured $G^*$ and the corresponding DART estimated values for the various asphalt binders evaluated. The DART testing was performed using the ADART#1C gage at the same testing frequency as the DSR, i.e., 1.59 Hz. Figure 72 presents a similar comparison for $\delta$. Based on the data and statistics presented in the figures, an unbiased and excellent agreement can be observed between the DSR and DART $G^*$ estimates. An unbiased and fair agreement can also be observed between the DSR and DART estimates of $\delta$–a parameter which is typically has a higher measurement error than the $G^*$.

Table 10. Evaluation space over which the FE-based data reduction scheme was validated.

<table>
<thead>
<tr>
<th>Binder Type</th>
<th>Test Temperature</th>
<th>DSR $G^*$, psi (GPa) at 1.59 Hz</th>
<th>DSR $\delta$, Degrees at 1.59 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-10</td>
<td>16°C (61°F)</td>
<td>411 (2.8)</td>
<td>61</td>
</tr>
<tr>
<td>AC-10</td>
<td>25°C (77°F)</td>
<td>66 (0.5)</td>
<td>78</td>
</tr>
<tr>
<td>AC-40</td>
<td>25°C (77°F)</td>
<td>149 (1.0)</td>
<td>67</td>
</tr>
<tr>
<td>AC-20 PAV</td>
<td>34°C (93°F)</td>
<td>248 (1.7)</td>
<td>45</td>
</tr>
</tbody>
</table>

The limited validation exercise thus establishes the ability of the DART device and the FE-based data reduction scheme to estimate asphalt binder properties that compare well with DSR-benchmark data.
Figure 71. Comparison of DSR Measured and DART Estimated G* at 1.59 Hz.

Figure 72. Comparison of DSR Measured and DART Estimated δ at 1.59 Hz.
5.4 Summary of Findings

A parametric study was conducted using the validated gage-asphalt continuum FE model to establish relationships between the two independent variables determined from DART testing—strain ratio and phase shift—and the two dependent variables of interest—\( G^* \) and \( \delta \) of the asphalt binder. Overall, the relationships established using the FE-based analytical framework for the ADART#1C gage were significantly different than those developed by Briar et al. (1976). The differences observed explain the mismatch in the estimated \( G^* \) values between the DART and the DSR thus establishing the ability of the new framework and data reduction scheme to provide better estimates of the asphalt binder properties of interest. The data reduction scheme was further validated by comparing the DART-estimated \( G^* \) and \( \delta \) with DSR estimated properties over a carefully selected range of asphalt binder \( G^* \) and \( \delta \) values and their combinations. The comparison showed that the DART estimated binder properties were in good to excellent agreement with those derived from conventional DSR testing.
CHAPTER 6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

The motivation for this study originated from the need for a low-cost, field implementable device capable of rapidly characterizing asphalt binders in the field for QA purposes. The intent was to investigate if the device could serve as a supplemental and surrogate test device to support specification compliance testing in support of the AASHTO M320 specification for PG graded asphalt binders. To this end, a piezoelectric duomorph gage, originally invented in the 1970s to monitor long-term viscoelastic properties of solid rocket propellant fuel, was redeveloped in the laboratory for application in asphalt rheology testing. The bench prototype system, dubbed the Duomorph Asphalt Rheology Tester or DART system, evolved as a result of a continuous refinement process that updated technologies used in the original development in the areas of component assembly, electronics, data acquisition, and data reduction.

The first part of the study involved finalizing the physical and operational characteristics of a prototype gage and the associated electronics that would give consistent outputs either when it is operating freely in air or when it is embedded in an asphalt specimen. For this purpose, circular piezoelectric duomorph gages, referred to herein as DART gages, of different diameters and thicknesses were manufactured and tested at various temperatures and frequencies. The piezoelectric DART gage outputs in response to an input AC drive voltage when operating freely in air in an unconstrained manner were compared to that of an asphalt embedded gage to estimate the properties of asphalt. Different gage instrumentation techniques (including strain gage types and signal conditioning and amplification devices) and piezo driving and grounding methods were experimented with to study their impact on the gage response. The embedded gage testing was performed in four unaged asphalt binders as well as one PAV aged asphalt binder. The following aspects of the DART system were evaluated during the testing performed—reasonableness of raw gage outputs, output repeatability, and system ruggedness. A user-friendly software interface was developed.
using the National Instruments software, LABVIEW, to facilitate gage excitation and data acquisition. The following main conclusions were drawn from these investigations:

- Equipment was assembled at a relatively low cost that shows considerable promise to test asphalt binders to determine their rheological characteristics.
- The DART gage and the associated electronics can withstand normal laboratory use for extended periods of time (over 2 years). This suggests that, with appropriate care, the device could also be used as a field QA device where the operating environment is expected to be more severe.
- The DART gage outputs—maximum bending strain and phase shift angle—were highly repeatable.
- DART gage responses are not dependent on the applied driving voltage level up to a maximum AC voltage of 120 Vp-p.
- DART gage responses were independent of frequency of the applied driving voltage up to a maximum frequency of at least 100 Hz when operating in air.
- Analysis of the raw DART gage data showed that it is sensitive to both the physical and mechanical properties of the asphalt medium.
- The DART strain and phase shift signals are unique to each asphalt type tested and can be used to establish a fingerprint of an asphalt binder (modified or neat) in the laboratory which, in turn, can be used to establish quality of the asphalt in the field using a statistical control chart.
- The sensitivity of the gage to the changes in the binder into which it is embedded seems to be a function of the ratio of the binder stiffness and the gage’s own flexural rigidity. Testing implied that different DART gage sizes, construction, and/or materials will be required for testing asphalt binders over the entire stiffness regime of relevance to the AASHTO M320 specification.
- Of the various gages developed in the study, the outputs of the ADART #1C type gage offered reasonable output over the largest possible range of stiffnesses of interest to unaged (tank) and PAV-aged asphalt binder testing. Specifically, this gage was sensitive to the asphalt medium when the storage modulus, G’, of the medium was in the range of 0.1 psi (0.69 kPa) to 4250 psi (29 MPa) and phase
angle was between 30° to 75°. While this covers a large range of binder types and temperature regimes of testing, it limits the applicability of the DART to perform the full suite of binder testing required by AASHTO M320 particularly at the high temperatures and cold temperatures.

- Testing revealed that the asphalt specimen size does not have a major impact on gage output at the frequencies of interest to the binder testing –1.59 Hz. However, the placement of the specimen in asphalt has an impact when the asphalt is stiffer. Therefore, a cylindrical specimen size of 4 inches (101.6 mm) for tank asphalts and 2 inches (50.8 mm) for PAV aged asphalt is recommended.

Based on the results of this investigation, a standard set of guidelines for asphalt binder testing using the DART were developed. These are listed below. The asphalt binder is expected to be within the linear viscoelastic range at these under these test conditions.

- The 1-inch diameter ADART #1C prototype gage with a total thickness of 20 mils or 0.51 mm (piezoceramic sheet thickness = 0.19 mm and stainless steel shim thickness = 0.13 mm) attached with Micro Measurements EA-06-125AC-350 strain gages (or equivalent) was adopted as the standard for asphalt binder testing.

- A 120 Vp-p AC voltage in conjunction with a 15 V DC bridge excitation voltage is recommended to drive the DART to obtain clean gage outputs at all test temperatures.

- The standard test frequency has been established as 1.59 Hz to match the AASHTO M320 specification DSR testing frequency.

- Testing in air should be immediately followed by testing in asphalt.

- Strain gage data from the DART gage should be collected after the first 10 cycles of loading the gage to avoid overheating of the piezoelectric materials due to the applied DC bridge excitation.

The next part of the study involved a more direct comparison of DART gage estimated G* and δ with those estimated from the DSR for an AC-20 reference binder. Comparisons were made for both the unaged and PAV-aged forms of this binder at a test frequency of 1.59 Hz.
The comparisons for the unaged binder were made over a temperature range of 5°C to 60°C while comparisons for the PAV-aged binder were made at 22°C and 30°C. The nomograph-based data reduction scheme proposed by Briar et al. (1976) was used to estimate G* and δ from the laboratory measured DART strain and phase shift responses. This data reduction procedure is based on linear elastic considerations of the gage and the continuum behavior extended by the elastic-viscoelastic correspondence principles to estimate viscoelastic material properties of the continuum into which the gage is embedded. A computer program written by Grosz (3) greatly facilitated in developing the nomographical solution space and automatically searching it for the desired asphalt properties. The following key conclusions were reached at the end of this comparison:

- Depending on the testing conditions—test temperature and aging of the asphalt sample—the G* values obtained from reducing the DART data for a reference AC-20 asphalt were either higher or lower than those estimated from a research grade DSR. Typically, the G* values were overestimated by the DART when compared to the DSR for the unaged binder and underestimated for the PAV aged binder.
- The estimates of phase angles from the DART when compared to those from the DSR showed a reasonable agreement.

The testing and evaluation clearly indicated the need to develop a more robust viscoelastic-based analysis procedure to replace the elastic solution proposed by Briar et al. (1976). Accordingly, a finite element model was configured to better understand the gage behavior when operating in an unconstrained manner and when embedded in an asphalt binder medium. Axisymmetric 8-noded solid elements were used to model the piezoelectric gage as well as the asphalt continuum. The gage was modeled as a linear elastic solid and the continuum as a viscoelastic medium. The problem was thus shifted from a piezoelectric domain to a mechanical domain in terms of materials characterization. Fluctuating electrical charges from an applied AC voltage field which cause the DART gage to bend were replaced with equivalent mechanical loads in the finite element analysis; the equivalency was determined experimentally. The DSR was used to test three asphalt binders to determine
complex moduli and phase angles over a range of temperatures and frequencies. Using these
data as inputs, the responses of the embedded gage were determined from the finite element
model. The DART gage outputs from the finite element model were then compared with
those observed in the laboratory. An excellent agreement was found between the finite
element predicted gage outputs and those determined experimentally at various temperatures
for all the binders tested thus validating the modeling approach. The limitation to the DART
gage operation in very stiff or very soft binders noted in the experimental analysis was also
confirmed by the theoretical investigation. The model was therefore deemed a good
candidate to develop a new data reduction scheme.

Utilizing the finite element model as the theoretical basis, a new nomograph-based data
reduction scheme, patterned after the one developed by Briar et al. (1976), was developed to
estimate asphalt binder properties of interest to this study (the DSR measured G* and δ) from
DART gage outputs. To develop this nomograph, a parametric study using the validated
finite element model was conducted to compute a database of gage responses for a set of
assumed asphalt material properties. The relationships between the key variables in the
nomograph developed from the finite element simulations for the ADART#1C gage were
found to be significantly different than those estimated using the analysis approach of Briar
et al. (1976). The finite element based nomograph was validated by comparing the DART
estimated G* and δ with corresponding DSR data which was used a benchmark. Although
the dataset used in the validation was limited, the DART estimates of G* and δ strongly
agreed with the corresponding DSR estimates. The DART may therefore be considered not
just as a fingerprint device but also as a device capable of directly providing the AASHTO
M320 specification’s DSR test parameters.

6.2 Recommendations for Implementation

Given that both the raw and reduced DART gage outputs are sensitive to the type of asphalt
medium and are consistent and repeatable, an immediate application area for the DART is to
use it as a surrogate device in the field to fingerprint asphalt for quality assurance purposes.
The DART is ideally suited for testing asphalt binders which may be produced by a supplier
through the blending of different binders or through blending modifiers into a virgin binder. The blended material can be accepted as produced by the supplier in accordance with the AASHTO M320. Immediately thereafter, the approved binder can be fingerprinted in the laboratory by testing it with the DART system to obtain either its strain and phase shift response signature or G*-δ signature at various temperatures and frequencies as desired within the operating constraints of the DART. These fingerprints can be stored and subsequently used to compare similar data obtained from DART testing conducted in the field on samples taken along its journey from the supplier to the job-site. On-site blending is done often e.g., for the production of certain types of modified binders. Since the testing is low-cost and nondestructive, it can be performed on a continual basis. At the plant, where the polymer or warm-mix additive is blended in line, samples can be taken at specified intervals and tested with the DART immediately once temperature stability is obtained. Differences in the DART “fingerprint” will immediately indicate the degree of blending compliance by comparing them with the values obtained from the approved laboratory blend. Control charts can be established to monitor the quality of the asphalt and take corrective action after additional verification is done using the AASHTO M320 specification equipment.

The following additional areas of work are recommended:

1. A laboratory DART bench prototype was developed and tested in this study. The laboratory prototype is bulky and cannot be taken to the field without suitable miniaturization. A miniaturized gage that is field-ready complete with built in electronics and software to drive the DART gage and to acquire and reduce its outputs should be developed.

2. There is a need to fully validate the finite element based nomographical procedure developed in this study to more comprehensively establish the ability of the DART to estimate G* and δ comparable to those obtained from the DSR. This can be accomplished by conducting more DART testing on binders other than those used in this research and using those in conjunction with the nomographical solution scheme developed in this study. Once the ability of the DART to estimate G* and δ are
firmly established, precision and bias statements can be prepared and a test standard
developed. Using the precision and bias statements as a basis, control charts can be
established to monitor the quality of the asphalt binder at various points along the
supply chain.

3. There is a need to conduct further testing of asphalt binders with the field-ready
apparatus and further analyze its outputs to understand how to detect significant
deviations from specification and to establish quality control and acceptance
standards.
REFERENCES


